A.6.0 Dilution Including Plume

A.6.1 Description

Contaminants released to the seabed will be carried by currents, which typically induce turbulence as they flow. This turbulence causes contaminants to be diluted as they mix with seawater. The distances over which contaminants are distributed (and diluted) depend on the currents passing over the release locations. In turn, the mixing rate and the volume into which the radionuclides are uniformly mixed will influence the distribution of contaminants in fish and other subsistence foods. To model exposure, a plume was defined in which fish are assumed to take up radionuclides from the seawater. The boundaries of the plume define the average concentration of radionuclides because they limit the mass of radionuclides and the volume in which the radionuclides are contained. The boundaries of the plume also define the number of fish exposed to that concentration because it is assumed that the density of fish per unit area is constant (Section A.10.2.3). Thus, a larger plume, defined by a greater dilution, will expose more fish than a smaller plume, but the exposure will be to a lower concentration of radionuclides, whereas a smaller plume, defined by less dilution, will expose fewer fish to a higher concentration of radionuclides. This section describes methods to calculate steady-state concentrations of radionuclides during dilution, either near Amchitka or in the Bering Sea. An EPA mathematical model (Jirka et al., 1996c) is used to predict the plume at each location.

A.6.2 Current Knowledge

There is sufficient information about the general direction and velocity of currents at each release site and general knowledge about other modeling parameters to enable dynamic modeling of radionuclide concentrations at specific locations near Amchitka. This was performed using EPA's Cornell Mixing Zone Expert System (CORMIX) model (Section A.6.2.1), and it constituted near-shore exposure (Section A.6.2.2).

CORMIX is an EPA-approved simulation and decision support system for environmental impact assessment of mixing zones resulting from continuous point source discharges. The system emphasizes the role of boundary interaction to predict mixing behavior and plume geometry. The CORMIX methodology contains systems to model submerged single-port and multi-port diffuser discharges as well as surface discharge sources. Effluents considered may be conservative, nonconservative, heated, or they may contain suspended sediments. Advanced information systems provide documented water quality modeling, *National Pollutant Discharge Elimination System* regulatory decision support, visualization of regulatory mixing zones, and tools for outfall specification and design.

For offshore exposure, a volume representing the Aleut culture and communication area will be represented by an exposure compartment used by the Office of Naval Research (ONR) in a risk assessment for radionuclides in Arctic waters (ONR, 1997). This exposure compartment is the upper 200 m of the southern part of the Bering Sea, an area that is approximately the same as the Aleut culture and communication area. Each is explained in the following sections.

A.6.2.1 CORMIX Model Selection and Model Description

The following characteristics were considered before selecting the appropriate model for this study:

- The model should provide conservative predictions.
- The model should be technically sound and capable of accounting for the key factors affecting the extent (geometry) of the plume (e.g., source condition, fluid stratification, near-field processes, and far-field processes).
- The model is a public domain model and is easily available.
- The model has been extensively verified.
- The model has received adequate peer review.
- The model is easy to use.
- The model is recognized and recommended by the EPA.

Based on the above characteristics, CORMIX was selected for the present study. The CORMIX software system is a series of models for the analysis, prediction, and design of aqueous toxic or conventional pollutant discharges into diverse water bodies (e.g., the ocean currents around Amchitka Island). It represents a robust and versatile computerized methodology for predicting both the qualitative features (e.g., flow classification) and the quantitative aspects (e.g., dilution ratio, plume trajectory) of the hydrodynamic mixing processes resulting from different water and radionuclide fluxes. CORMIX can predict the extent of a plume for submerged single-point source and submerged multipoint diffuser sources. It can adapt to fluid stratification, including salinity and density.

CORMIX can also adapt to initial and distant mixing zones. The initial mixing zone occurs near to the contaminant source, and the zone is controlled by near-field processes. The distant mixing zone occurs away from the contaminant source, and the zone is controlled by far-field processes.

CORMIX was developed under several cooperative funding agreements between EPA and Cornell University during the 1985 to 1995 time period. It is a recommended design tool in key guidance documents (EPA 1991a, EPA 1991b; Jirka 1992) on the permitting of industrial, municipal, and other nonpoint source discharges to receiving waters. CORMIX has been extensively verified by the developers through comparison of simulation results to available field and laboratory data on mixing processes (Doneker and Jirka, 1990; Akar and Jirka, 1991; Jones et al., 1996a; Jirka et al. 1996a and b). It has also undergone extensive independent peer review in journal proceedings (Doneker and Jirka, 1991; Jirka and Doneker, 1991; Jirka and Akar, 1991; Aker and Jirka, 1994; Aker and Jirka, 1995; Mendéz-Diaz and Jirka, 1996; Jones et al., 1996b; Jones and Jirka, 1996; Nash and Jirka, 1996). The EPA's established policy is to make the software freely available to all potential users through its modeling software distribution facility at the EPA Center for Environmental Assessment Modeling (CEAM) in Athens, Georgia. In addition, previous application has proven this code is highly user-interactive and offers sufficient flexibility to a modeling effort in the Bering Sea and Pacific Ocean off of Amchitka Island.

A.6.2.2 Near-Shore Exposures in Plumes

Groundwater flow through Amchitka Island eventually discharges from the seafloor into Amchitka marine waters. The groundwater modeling predicts a distribution of possible discharge locations for groundwater originating from the test cavities. A discharge location midway between the 5th percentile lower bound and the 95th percentile upper bound of the predicted discharges (see Table A-2) was chosen for each of the three sites, with the discharge rates set equal to a mean value estimated from the groundwater model parameters. The distribution of contaminant concentration in the water was simulated with the EPA mixing model, CORMIX (Jirka et al., 1996c), which uses a variety of hydrodynamic modules to predict mixing and advection of the discharge into a plume of contamination. As explained above, CORMIX is distributed by the EPA's CEAM and is routinely used for simulating mixing of underwater discharges with the ambient water. Output of the model varies with each module but typically consists of concentration and horizontal and vertical extent of the plume. These results have been used to define the spatial limits of the plume and to compute the volume of the plume and the average contaminant concentration within these limits.

Calculating exposures requires a method to convert radionuclide flux to concentration in some defined volume of seawater. That volume, called the plume, may be defined as a particular area or volume or it may be defined as a volume whose boundaries are set where the initial discharge is diluted by a certain amount. These definitions are not predetermined because no matter what they are, the model can always calculate a concentration, no matter how low, outside the boundary. For this risk assessment, the boundary was set as a dilution factor to make the plumes more consistent among sites. The size of the plume increases as the dilution factor decreases; that is, a plume defined by a 10^{-7} dilution is larger than a plume defined by a 10^{-6} dilution.

Because the concentration of radionuclides decreases as the plume size increases, there is a tradeoff between the average concentration and the size of the plume to which fish are exposed, so the concentration in fish decreases as the plume size increases. The plume size is used as a fraction of the exposure area, so the fraction of fish exposed increases as the plume size increases. For this risk assessment, a dilution factor of 10^{-7} was chosen. Outside the boundary, concentrations are less than one ten-millionth of the initial discharge concentration, and uptake at those concentrations are overshadowed by uptake at concentrations within the plume. Therefore, the plume boundary is judged to be sufficiently conservative.

Due to the limited knowledge of velocity, direction, and time dependence of currents at each of the three potential release locations, steady-state simulations were performed of the transport of contaminants contained in groundwater discharges. The discharges were assumed to be from a single discharge point for each simulation. A single discharge point provides a more conservative evaluation than a multi-point discharge because the initial concentration is higher with a single discharge point. Pertinent input data required for the simulations are displayed in Table A-4.

For the example model run presented here, the discharge rates chosen for each site were based on DRI estimated values. DRI has estimated that the simulated groundwater discharge rates averaged 72.5 cubic meters per day (m^3/d) at Cannikin, 24.3 m^3/d at Long Shot, and 24.8 m^3/d at Milrow. To determine whether the CORMIX simulation outcome is sensitive to the groundwater discharge rates, CORMIX simulations with discharge rates equal to the upper and the lower 95 percent confidence

Table A-4
Parameter Values Used in CORMIX Modeling

Parameter	Cannikin	Long Shot	Milrow	
			Without Kelp	With Kelp
Water depth (m)	68.6	30.5	23.5	23.5
Water velocity (cm/s)	32	32	30	10
Distance of discharge from shore (m)[a]	2,997	2,024	1,984	1,984
Wind speed (m/s)[b]	8.1	8.1	8.1	8.1
Darcy-Weisbach friction factor f	0.02	0.02	0.02	0.02
Water density at surface (kg/m^3)[d]	1,026	1,026	1,026	1,026
Water density at bottom (kg/m^3)[d]	1,026.1	1,026.1	1,026.1	1,026.1
Discharge rate (m^3/d)[e]	72.5	24.4	24.8	24.8
Discharge density (kg/m^3)[f]	1,000	1,000	1,000	1,000

[a]CORMIX assumes a rectangular cross-section across the current, and the distance from the shore may be different from the physical distance in order to simulate interaction with a sloping bottom. Early simulations indicated that the region of the plume with a dilution of 10^{-6} or less would not interact with the bottom for a stratified water body. Therefore, these distances are the physical distances to the discharge locations.
[b]Average wind speed computed from wind roses (Armstrong, 1977).
[c]Darcy-Weisbach friction factor (f), generally specified for the ambient roughness characteristics for the bounded case (Jirka et al., 1996c).
[d]Water density at the top and bottom were estimated from temperature and salinity cross-sections (McAlister and Favorite, 1977).
[e]Based on a prediction for the Cannikin site by groundwater modeling.
[f]Assumed for cold, fresh groundwater.

m = Meter
kg/m^3 = Kilograms per meter
cm/s = Centimeters per sec
m^3/d = Cubic meters per day
m/s = Meters per second

limits of the mean discharge rates for all the three locations (i.e., Cannikin, Long Shot, and Milrow) were performed. The confidence interval was defined as

$$\mu \pm 1.96 \times \sigma \div \sqrt{n}$$

Where:

μ	=	Groundwater modeling mean discharge rate
1.96	=	t-statistic for 95 percent confidence interval
σ	=	Standard deviation of modeled discharge rates
n	=	Number of times the groundwater model was run

Based on these simulations, it was concluded the average concentration for a particular dilution scenario will not be impacted within the 95 percent confidence limit of the mean discharge rate. For example, the predicted average concentration for a 10^{-7} dilution scenario at Cannikin is 0.26, with the discharge rate varying from 66.6 m^3/d (lower concentration limit) to 78.4 m^3/d (upper concentration limit).

All the simulations were performed for stratified conditions. In addition, the simulations of a stratified ocean were repeated with a wind speed of 3 meters per second (m/s) as a sensitivity analysis.

Output from the CORMIX model consists of three different possible descriptions of the plume. The location of the centerline of the plume is defined by longitudinal, vertical, and lateral coordinates. As the plume moves through the ocean water, a sequence of computation modules is chosen by the internal logic of CORMIX. Depending on which module in CORMIX has been used, the concentration and dimensions of the plume at each location along the axis of the plume are specified by one of the following:

1. Centerline concentration and radial distance to a concentration that is 1/e (e = base of the natural logarithms) of the centerline concentration. The plume is circular and has a Gaussian concentration distribution:

$$C = C_0 e^{-(\frac{r^2}{B^2})},$$

Where:

- C_o = The centerline concentration
- r = Distance from the centerline
- B = Distance to a concentration of 1/e of C_o

2. Centerline concentration, vertical dimension, and horizontal half-width to points where the concentration is 0.46 of the centerline concentration. The distribution is Gaussian in both the vertical and horizontal directions so that a boundary of constant concentration is an ellipse.

3. Vertical dimension, horizontal half-width, and average concentration over the cross-section of the plume. Numerous simulations and curve-fitting procedures allowed these results to be converted to an approximation of the form of the results in Item 2 above.

More detailed information on the interpretation of the model output is available in the CORMIX users manual (Jirka et al., 1996c). For purposes of this assessment, the plume is defined as the region in which the concentration of radionuclides is equal to or greater than 10^{-7} of the concentration in the groundwater discharged into the sea. The concentration of the groundwater discharge was set at a nominal 1×10^{-6} units so that the plume is the region enclosed by the surface on which the concentration is 0.1 (i.e., 10^{-7} times the starting concentration). The dimensions of the plume cross-section, the area of the cross-section within the 10^{-7} dilution boundary and the average concentration within that boundary, were determined at each point along the plume axis where model output was available.

The total mass of contaminant and the total volume within the plume defined by the 10^{-7} dilution boundary were then computed by integrating along the centerline of the plume assuming that the cross-sectional area and concentration vary linearly between adjacent cross-sections. The results of these analyses are summarized in Table A-5 and in Figures A.5 through A.8.

The effect of wind speed in stratified conditions is slight except at the Milrow site with kelp (Figure A.8). This site is shallow and the effect of kelp is modeled by reducing the velocity of the ambient water by a factor of three. Because of the slow velocity, more mixing and dilution occur over a shorter distance at a higher wind speed, and the volume of the contaminated plume is reduced. Average concentration within the 10^{-7} plume boundary is rather uniform, ranging from 0.264 at Cannikin to 0.27 at Long Shot and Milrow, as can be seen in Table A-5. In addition, the figures show the same behavior for the intermediate plumes defined by 10^{-6} and 10^{-5} dilution boundaries. For Milrow with kelp, because of low water velocity, the concentrations are generally higher. It may be noted that CORMIX limited prediction to 3×10^{-7} for Milrow with kelp because the plume hits the shore at greater dilution. However, the results of risk modeling using the mean concentrations (Table A-7 and Table A-8) were the same whether or not kelp was assumed to be present.

The volume of the plume shows considerable variation with the combination of depth, current speed, wind speed, and discharge rate. For example, the volume of the plume within the 10^{-7} plume boundary varied from 1.34×10^{7} m^3 for Milrow with kelp to 1.79×10^{8} m^3 for Cannikin.

The figures show both longitudinal sections and plan views of the limits of the plumes defined by the 10^{-7} dilution boundary.

Table A-5
Summary of Dispersion Modeling for Discharges in the Amchitka Marine Environment

Test Site	Discharge Rate (m^3/day)	Dilution Factor at the Plume Perimeter	Average Concentration Within the Plume (unit)	Mass Within the Plume (unit)	Volume Within the Plume (m^3)	Plan Area Within the Plume (m^2)	Mass Within the Plume (%)	Downstream Distance (km)
Cannikin	72.5	1.0E-05	1.98E+01	2.35E+06	1.18E+05	4.20E+04	3.2%	1.9
	72.5	1.0E-06	2.50E+00	1.26E+07	5.02E+06	1.26E+06	17.2%	8.7
	72.5	1.0E-07	2.64E-01	4.72E+07	1.79E+08	3.28E+07	64.7%	28.3
Long Shot	24.3	1.0E-05	1.99E+01	3.83E+05	1.93E+04	1.17E+04	1.6%	1.3
	24.3	1.0E-06	2.47E+00	2.13E+06	8.62E+05	3.27E+05	8.7%	4.6
	24.3	1.0E-07	2.70E-01	8.25E+06	3.05E+07	7.20E+06	33.8%	15.2
Milrow	24.8	1.0E-05	2.00E+01	4.88E+05	2.45E+04	1.43E+04	2.0%	1.4
	24.8	1.0E-06	2.50E+00	2.65E+06	1.06E+06	4.04E+05	10.7%	4.6
	24.8	1.0E-07	2.70E-01	9.29E+06	3.43E+07	7.94E+06	37.4%	15.4
Milrow with Kelp	24.8	1.0E-05	2.86E+01	1.74E+06	6.08E+04	3.90E+04	7.0%	0.9
	24.8	1.0E-06	2.94E+00	5.91E+06	2.01E+06	1.02E+06	23.8%	3.7
	24.8	3.0E-07	8.44E-01	1.13E+07	1.34E+07	6.17E+06	45.6%	8.1

Figure A.9 shows rectangles to indicate the locations of three-dimensional (3-D) cutaway volumes. Figure A.10 shows a perspective cutaway view for Cannikin. Figure A.11 shows the same type of information for Long Shot, and Figure A.12 shows this for Milrow. In addition, Figure A.13 shows a duplicate perspective cutaway view for Milrow when kelp is assumed to retard the near-shore current by three-fold (Jackson and Winant, 1983).

To calculate the dilution of radionuclides, it is necessary to derive a dilution factor. This factor converts radionuclide flux (the rate of release of a radionuclide in pCi/d) to a concentration in the plume (picocuries per cubic meter [pCi/L]). The calculation is done by dividing the average concentration in the plume (e.g., 0.27 picocuries per cubic meter [pCi/m^3] for Long Shot) by the nominal total flux (1×10^6 $pCi/m^3 \times 24.3$ m^3/d). The result for Long Shot is $0.27/2.44 \times 10^7 = 1.11 \times 10^{-8}$ pCi/m^3 per pCi/d or 1.11×10^{-11} pCi/L per pCi/d. Similarly, the dilution factors at the other locations are 3.6×10^{-12} for Cannikin, 1.09×10^{-11} for Milrow without kelp, and 3.40×10^{-11} for Milrow with kelp.

A.6.2.3 Offshore Exposure

Offshore exposure occurs in a very large volume of water that represents the Aleut culture and communication area (Figure A.14). The information necessary to calculate concentrations in the cultural area is not available, but alternative information is available. Information used for a risk assessment by the ONR for radionuclides released into the sea by former Soviet Union naval activities (ONR, 1997) includes three compartments of various sizes in the Bering Sea. They are the northern Bering Sea (all depths), the southern Bering Sea upper layer (upper 200 m), and the southern Bering Sea lower layer (deeper than 200 m).

The southern Bering Sea compartments include the Aleutians, west of approximately the location of Umnak Island, and extend on the south side to Siberia midway down the Kamchatka Peninsula (about 55° N) and on the north side to Siberia about 62.5° N. They have roughly the same area as the Aleut culture and communication area (Figure A.14). Therefore, the upper layer of the southern Bering Sea compartment was used as an exposure compartment to approximate steady-state distribution of radionuclides potentially released from Amchitka undersea sources in the entire Aleut cultural and communication area. This compartment has a volume of approximately 5.5×10^{17} liters (5.5×10^{14} m^3) (ONR, 1997).

The ONR model includes the rates at which water moves into and out of the Bering Sea compartments. There is relatively little transfer of water from the upper layer (upper 200 m) to the lower layer (ONR, 1997), and much of the subsistence food, fish and mammals, and commercially important fish are found in the upper 200 m of the sea (Simenstad et al., 1977). Therefore, the upper Bering Sea compartment was chosen as the exposure compartment for subsistence consumers in the Aleut culture and communication area. The Bering Sea is also a widely used fishery, so the upper Bering Sea compartment was also chosen as the exposure compartment for consumers of commercial catch.

Calculating the cancer risk based on dilution of radionuclides in the offshore compartment requires calculation of the dilution factor. The steady-state concentration of radionuclides in the upper south Bering Sea compartment was calculated using a model in which an equilibrium is reached (i.e., the radionuclide flux entering the exposure compartment is equal to the radionuclide flux leaving the compartment). Fluxes of water into and out of the exposure compartment and the neighboring compartments were taken from ONR (1997). It was assumed that the radionuclide flux leaving the compartment is equal to the radionuclide concentration multiplied by the water flux leaving the compartment. On each day, the total mass of the radionuclide in the exposure compartment is equal to the total mass on the previous day, plus the radionuclide flux for one day from the releases, minus the radionuclide flux leaving the compartment on that day. That total mass is divided by the volume of the compartment to calculate the concentration. This calculation was done for many successive time periods until equilibrium was reached (i.e., the final concentration no longer changed from day to day [about 8 years]).

The concentration modeling was done by using a flux of 1 pCi/d. The calculation yielded a dilution factor that can be applied for any radionuclide flux. The dilution factor was calculated to be 8.5×10^{-16} pCi/L per pCi/d of release.

A.6.3 Discussion of Uncertainties

Dilution factors are calculated for a nearshore exposure area and for an offshore exposure area. Their uncertainties are described below.

Parameters whose uncertainty affects the calculation of dilution factors for nearshore dilution include the CORMIX model, and the modeled groundwater discharge rate. Uncertainties in the CORMIX modeling results come from uncertainty in the input parameters. The input parameters are best scientific estimates of conditions at Amchitka, based on site-specific information about water depth, water velocity, distance of discharge from shore, wind speed, and water density.

Groundwater discharge rates were calculated by the groundwater model as mean values, so they could have higher or lower values. Variability in parameters has little effect on the outcome of the risk assessment. In particular, comparing the CORMIX modeling results using the mean groundwater discharge rate to the results using the upper and lower 95 percent confidence limits of the mean showed no effect on the concentration of radionuclides in the plume. Varying the wind speed also had little effect on the results except that under the slow current conditions at Milrow with kelp, a higher wind speed reduced the volume of the plume and, therefore, the exposure because of more rapid mixing.

The dilution factor for the nearshore exposure in plumes was calculated by dividing the concentration in the plume given by the CORMIX model by the estimated groundwater discharge rate. As stated in Section A.6.2.2, the concentration in the plume is based on scientific judgment. The groundwater discharge rate is the mean of groundwater modeling results, so the actual discharge rate could be higher or lower than the value used to calculate the dilution factor, changing the dilution factor. If the dilution factor is calculated for Cannikin, for example, by using the concentration in the plume and a range of groundwater discharge rates plus and minus one standard deviation from the mean, the result is dilution factors that are within a factor of four of the factor used. Therefore, the effect of uncertainties about the concentration in the plume and the groundwater discharge rate is expected not to be large.

The dilution factor for the offshore exposure compartment (Section A.6.2.3) was calculated with a multi-compartment model that assumed seawater flux rates into and out of ocean volumes (compartments) defined by ONR (1997). There is uncertainty that the same dilution factor applies to the Aleut culture and communication area because the ONR data are for the entire Bering Sea. Seawater flux data into and out of the Aleut culture and communication area were not available to construct a multi-compartment model specific for that area. The risks for the base case in Scenarios 7, 8, and 9 (fish subsistence diet, marine mammal subsistence diet, and commercial catch diet, respectively) are so low that an overestimate of dilution (underestimate of concentration) of one or two orders of magnitude would still predict risks far below the EPA threshold.

A.6.4 Implementation

The various models described above were used to calculate dilution (see Table 3 in the main text) for small, near-shore plumes and large offshore volumes. Near-shore predictions depend on EPA's CORMIX model (Jirka et al., 1996c). Steady-state concentrations of radionuclides diluted in the offshore compartment were calculated from the radionuclide flux into the compartment, the volume of the compartment, and the water flux into and out of the compartment.