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Measurements of Radionuclides in Par Pond Sediments with an Underwater HPGe Detector^(U)

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Measurement of Radionuclides in Par Pond Sediments with an Underwater HPGe Detector

Executive Summary

Savannah River Site (SRS) effluent gamma emitting radionuclides in Par Pond sediment were examined in situ with an underwater HPGe detector prior to and following a 19 ft drawdown of the pond in 1991 to address dam repairs. These measurements provide a map of the ^{137}Cs concentrations of the pond sediment, indicating that 9.4 ± 1.5 Ci is exposed by the drawdown and that 46.6 ± 7.2 Ci is the entire pond inventory. The highest individual ^{137}Cs concentration was $25 \mu\text{Ci}/\text{m}^2$ for the exposed sediment and $50 \mu\text{Ci}/\text{m}^2$ for the entire pond. The results are consistent with parallel studies conducted by SREL, as well as historical data.

Aside from ^{137}Cs , the only other SRS-produced isotope observed was ^{60}Co , with activity of only about 1% of that for ^{137}Cs . This observation was also confirmed in grab samples of pond sediment

and vegetation, which were returned to the laboratory for ultra-low-level gamma spectrometry analysis.

A special effort was required to calibrate the underwater HPGe detector, where both measurements and calculational models were used. The effects of sediment depth profiles for density and ^{137}Cs concentration were addressed in the calibration. Calibration factors for sediment surface concentrations ($\mu\text{Ci}/\text{m}^2/\text{cpm}$) and sediment mass concentrations ($\text{pCi}/\text{kg}/\text{cpm}$) were obtained. In general, the $\mu\text{Ci}/\text{m}^2/\text{cpm}$ factor is recommended, as the $\text{pCi}/\text{kg}/\text{cpm}$ factor depends on the depth location of the sediment of interest. However, a $\text{pCi}/\text{kg}/\text{cpm}$ factor, which is dependent on the depth within the sediment, is presented to address dose calculations that require it.

Introduction

In March 1991 a depression was discovered on the downstream side of Par Pond Dam. Subsequently, plans were initiated to lower the pond level by 19 ft to provide assurance against a dam failure and to allow for repairs. In this drawdown, a 528 hectare area of pond sediment was to be exposed, which is 50% of the normal 1057 hectare pond area when at full pool of 200 ft msl. Because these sediments were known to contain SRS-produced radionuclides, it was important to predict what their radiological impact would be prior to the drawdown, which was completed in September 1991.

The Par Pond sediments were expected to be dominated by ^{137}Cs , based on historical data.¹ During R Reactor operations between 1954 and 1964, about 222 Ci of ^{137}Cs were released to the Lower Three Runs System, which served to fill Par Pond in 1958. Because cesium favors collection in sediment rather than water, much of the ^{137}Cs remains in the pond sediment. As of 1991, the released ^{137}Cs had decayed to 112 Ci, but only 71 Ci was projected for Par Pond, Pond C, and the Lower Three Runs Creek System. Evaluations for associated smaller ponds and transport to the river account for the remainder. Because measurements indicated 12 Ci of this

^{137}Cs was in Pond B,² it was reasonable to consider that nearby Pond C and Lower Three Runs Creek would have at least this amount, suggesting an upper limit of 59 Ci for Par Pond. Also, the large area of Par Pond suggested that at least half of the 71 Ci might be expected to reside there, implying a lower limit of 35 Ci for Par Pond. Thus, it could be reasonably predicted that Par Pond sediment should contain 35-59 Ci of ^{137}Cs in 1991.

The present work sought to validate the above Par Pond information, and to extend it to appraise the impact of the ^{137}Cs in sediments to be exposed upon drawdown. An underwater HPGe detector was used to map the sediment ^{137}Cs on the pond bottom. A calibration factor was developed to convert the observed ^{137}Cs count rates to activity per sediment surface area. Initial work in July 1991 conducted mappings down to pond depths of 28 ft, to examine the sediments to be exposed with the 19 ft drawdown to 181 ft msl. Followup work during September to November examined the remainder of the pond, including maximum depths to 142 ft msl, so that the earlier historical information could be validated.

Methods

Overall Approach

An aerial view of Par Pond in August 1991 during drawdown is shown in Figure 1, where beachlike areas about the pond are the exposed sediment. In July, prior to significant drawdown, an underwater HPGe detector mapped the ^{137}Cs detected in these sediments and those down to 172 ft msl, and post-drawdown measurements mapped the rest of the pond sediments. Measurements were made with the detector on the pond bottom for representative transects of the pond at 3 ft depth intervals. Selection of these transects was partly guided by 1962 mappings with an underwater G-M counter,³ and the resulting HPGe measurements were evaluated as being representative of the pond relative to the goals of the present study.

Additional data was also sought during the study. The sediment temperature and underwater vegetation were recorded for some of the underwater HPGe measurements, to examine their consistency with previously noted ^{137}Cs correlations.² At various locations, grab samples of sediment and underwater vegetation were collected for low-level gamma spectrometry at the Savannah River Technology Center/Environmental Technology Section (SRTC/ETS) facilities. Such samples would help reveal any other SRS-produced gamma-emitting radionuclides in the pond environment. The sediment samples would also provide some information on the detector calibration; however, data from segmented core samples collected and analyzed by Savannah River Ecology Laboratory

(SREL) provided the most detailed information for the calibration.⁴

Underwater HPGe Detector

The underwater HPGe detector operated from a pontoon boat, as shown in Figure 2. The detector has about 30% efficiency, relative to standard comparison with a 3"x3" NaI detector. Figure 3 is a photograph of the detector and its liquid nitrogen dewar, both of which are contained within a screen housing. The housing serves to protect the detector from impact damage and also defines the sediment counting geometry. The detector is lowered by a winch through a trap door of the boat deck. An initial winch only reached depths of 30 ft, but a later replacement winch extended the measurements down to 58 ft, the deepest pond depth. With the detector lowered to the bottom sediment, one-minute HPGe spectra were collected, yielding the count rate of the 662 keV gamma of ¹³⁷Cs. The pond depths were determined with a Lowrance depth finder.

Underwater operation of the HPGe detector requires appropriate electrical cabling and venting of the evaporated liquid nitrogen. Both are provided through waterproof tubes extending from the detector to the deck. The detector preamp cables for power, high voltage, and signal output are all contained in a single tube. On the deck these cables are connected to standard NIM electronics, where the preamp signal pulses are amplified and collected as gamma spectra using a COMPAQ computer configured as a multichannel analyzer with an ACETM card. A 5 kVA gasoline generator energizes an uninterruptable power supply, which in turn provides reliable clean power for the electronics.

Ultra-Low-Level Gamma Spectrometry

Grab samples of vegetation and sediment were analyzed in the SRTC facilities, which include the Ultra Low Level Counting Facility (ULLCF) and the Underground Counting Facility (UCF).⁵ The vegetation samples were examined in the ULLCF, and the sediment samples were analyzed in the UCF. Vegetation samples were ashed to smaller volumes of 5-10 cm³ to enhance detection efficiency; then they were counted for about 6 hr within standard 33 mm diameter counting vials. Sediment samples of about 300g were placed in standard 64 mm diam counting vials, and counted overnight or longer in the UCF.

The ULLCF is a ground-level counting facility contained within a chamber with 12 in walls of pre-WWII steel. The air of the facility is filtered to remove natural background particulates. HPGe detectors with standard efficiencies ranging from 8.8% to 16.0% were used in counting the vegetation samples.

The UCF is 50 ft below ground and constructed with low background materials. Pre-WWII steel comprises the 4 in walls of the counting chamber, which is shielded by 4-7 ft of specular hematite. The total overburden is equivalent to 104 ft of water shielding, which reduces the cosmic background by an order of magnitude. The facility operates as a Class 10,000 clean room, whereby airborne particulates are removed by filtering. The very stable spectrometry electronics use an uninterruptable power supply to protect against data losses during extended counting times. A HPGe detector with 90% standard efficiency counted the sediment samples. To remove radon background, the shielded sample cavity of the detector is purged with nitrogen that evaporates from its dewar. The detector is also enclosed in an active plastic scintillator shield, which vetoes counting during short intervals in which cosmic-ray background is detected.⁶

Measurements

Underwater HPGe Detector

Measurements on Par Pond were conducted for the 9 transects given in the map of Figure 4. Additional measurements in the mouth of the middle arm (transect 10, not shown on map), examined a maximum activity area known from earlier studies. The raw data from these measurements are recorded in Appendix A, where each measurement is characterized by its location coordinates, pond depth, and ^{137}Cs count rate measured by the underwater HPGe detector. For measurements at pond depths down to 28 ft, sediment temperature and vegetation observations are also recorded. Only one minute of counting was required to obtain suitable count-rate statistics.

Gamma-ray spectra measured with the underwater HPGe detector are given in Figure 5. Aside from ^{137}Cs , the only other man-made radionuclide detected was ^{60}Co . This was also the case for the vegetation and sediment samples that were returned to the laboratory for counting.

For an individual transect, the count-rate data scatter noticeably, as shown in the example in Figure 6; however, trends in the data are still recognizable. Overall, each transect shows that sediment ^{137}Cs increases with pond depth. Figure 7 displays this overall trend better by plotting the ^{137}Cs count rates of all transects of Figure 4 as a function of pond depth. Smoothed normal and geometric averages of count rates exhibit the trend more clearly in Figure 7. Here, each average includes a single point and 18 adjacent points (9 above and 9 below) at monotonic depths. Corresponding smoothed normal-average depths are assigned to each smoothed count-rate.

Consistency of Underwater HPGe Data

Various quality checks were applied to appraise the measurements. Suspiciously low count rates were remeasured after slight repositioning of the detector on the bottom, to assure that obstructions such as stumps did not displace the detector from the bottom sediment. After each measurement, any muddy sediment sticking to

the bottom screen was removed to prevent cross-contaminating measurements from one site to another.

Tests were also conducted to appraise the adequacy of the data for its intended application. As shown in Figure 4, ^{137}Cs count-rate averages for half-transects (shore-to-deepest depth) were calculated to examine variations as a function of pond location. Reasonable monotonic trends with location are observed in the Figure, and the maximum/minimum for these values is only a factor of 4. Thus, the transects were appraised as providing a representative sampling of the pond.

In Figure 7 a small dip in count rate is noted in the smoothed data for sediment depths of about 17 ft. Such observations have been noted earlier and are correlated with the limit of underwater vegetation.² Such a correlation also existed in the present study, as noted in Figure 8a, where the average occurrence of observed vegetation is plotted as a function of depth. The 17 ft depth for the vegetation limit also corresponds to the point of rapid decrease in dissolved oxygen, deduced from direct measurements³ and the corresponding dropoff in the average temperature measurements shown in Figure 8b. Details on the average vegetation and temperatures of Figure 8 are given in Appendix B.

Low-Level HPGe Laboratory Measurements

Measurements for the samples returned to the ULLCF and UCF are summarized in Table 1. Other than ^{137}Cs , the only man-made isotope observed was ^{60}Co , which had only about 1% the intensity of the ^{137}Cs . The ^{60}Co and ^{137}Cs have respective half-lives of 5.3 and 30.2 years, which are much longer than other gamma-emitting nuclides that were released to the pond about 30 years earlier. Example gamma spectra for these samples are given in Figure 9. It should be noted that the present studies were not appropriate for detecting long-lived pure beta isotopes such as ^{90}Sr and low-yield gamma emitters such as isotopes of U and Pu.

Data Transformation - Calibrations

The above ^{137}Cs count-rate (cpm) measurements with the underwater HPGe detector required transformation to activity/area ($\mu\text{Ci}/\text{m}^2$), before the pond inventory of ^{137}Cs could be quantified. In actuality, each sediment measurement location should have a unique conversion factor ($\mu\text{Ci}/\text{m}^2/\text{cpm}$), because the factor depends on the depth profile of ^{137}Cs within the sediment and sediment density profile. It was suggested that peak/Compton correlations of the measured spectra might guide individual corrections. However, the overall low counting statistics implied that this approach would be unfruitful. It was decided to develop a single global conversion factor, which would be modeled for a representative average sediment. Although an error would be introduced for individual measurements converted with this factor, the errors for numerous averaged measurements, as given in Figure 7, tend to cancel.

Model for Conversion Factor ($\mu\text{Ci}/\text{m}^2/\text{cpm}$)

The conversion factor for ^{137}Cs activity required efficiency calibrations for its 662 keV gamma. Referring to Figure 10, the efficiency for a point in the sample is

$$\epsilon(r, z) = \epsilon_A(0, 0) \frac{z_0^2}{(z + z_0)^2 + r^2} \exp(-\mu_w l_w - \bar{\mu}_s(z) l_s) \quad (1)$$

where $\epsilon_A(0, 0)$ is the point ($r=0, z=0$) efficiency measured in air, and μ_w and $\bar{\mu}_s(z)$ are the gamma attenuation coefficients for water and sediment. Sediment core measurements⁴ provided an average density $p_s(z)$ so that

$$\bar{\mu}_s(z) = z^{-1} \int_0^z \mu_s(z') dz' = z^{-1} \int_0^z p_s(z') \sigma dz' \quad (2)$$

where σ is the mass attenuation coefficient.

The ^{137}Cs count rate R is an integral over the volume producing the rate,

$$R = A \int_0^h \int_0^a \bar{P}(z) I_\gamma \epsilon(r, z) 2\pi r dr dz, \quad (3)$$

wherein the gamma emission rate per sediment volume is $A \bar{P}(z) I_\gamma$ where A is the ^{137}Cs decay rate per sediment surface area, $\bar{P}(z)$ is the average ^{137}Cs probability per z -increment, and I_γ denotes the 662 keV gammas per ^{137}Cs decay. Twelve individual $P(z)$ from core data² yielded $\bar{P}(z)$, which defined integral limit $h = 38$ cm. With radial limit $a = 70$ cm, integral calculations were within 1% of those for $a = \infty$. Using this information in Eq.(3) yielded a value of $A/R = 0.0171 \pm 0.0027 \mu\text{Ci}/\text{m}^2/\text{cpm}$ for transforming count rates to activities, where the A/R uncertainty was obtained as follows.

The average depth distributions for ^{137}Cs probability $\bar{P}(z)$ and sediment density $p_s(z)$ are given in Figure 11. The error for the A/R conversion factor was calculated by examining the conversion factors for the individual $P(z)$ used in the average. The variations in the twelve $p_s(z)$ were negligible relative to those of $P(z)$. Further details on the calculations, including the code describing the numerical integrations, are given in Appendix C.

Alternative Conversion Factor ($\text{pCi}/\text{kg}/\text{cpm}$)

Some of the preliminary analyses of these studies had used a ^{137}Cs conversion factor in units of $\text{pCi}/\text{kg}/\text{cpm}$, which was determined by using grab samples taken at locations where the underwater detector had measured ^{137}Cs count rates. These grab samples (15.6 cm x 15.6 cm area, 8.6 cm depth) were taken with a dredge, homogenized, and returned to the laboratory for analysis in the UCF to determine their ^{137}Cs concentrations. The resulting ratios of concentration (pCi/kg) to count rate (cpm) yielded an average ratio of 85 $\text{pCi}/\text{kg}/\text{cpm}$.

Although a pCi/kg/cpm conversion factor is easy to measure, it is generally inappropriate for accurately describing the ^{137}Cs within the sediment. Because ^{137}Cs varies with sediment depth, as shown in Figure 11a, the grab sample provides only an average pCi/kg for the sediment sampled. No information is obtained for the ^{137}Cs at deeper depths into the sediment. Also, it is difficult to assure that the sediment sample is taken exactly at the same location as the underwater HPGe. The preliminary 85 pCi/kg/cpm conversion factor did provide rough estimates (factor of 2 low) of the Par Pond ^{137}Cs inventory, which were primarily limited by the uncertainty in the effective sediment thickness.

Overall, conversion factors using area concentrations are recommended over those using volume or mass concentrations, because the latter are dependent on depth location within the sediment. The depth effect for Par Pond sediments is illustrated in Table 2, where the area

concentration conversion factor for this work has been transformed to mass concentration factors as a function of depth. Table 2 utilizes the ^{137}Cs probability and sediment density profiles of Figure 7 to yield the ^{137}Cs conversion for wet sediment. This profile information, as well as that for dry sediment, are included in the table. The table illustrates that a wet grab sample retrieved down to a sediment depth of 10 cm would include sediment with conversion factors ranging from 57 to 154 pCi/kg/cpm, yielding an overall average of 108 pCi/kg/cpm. If the sediment were uncovered in drawdown and dried out, the top layer would have a conversion factor of 456 pCi/kg/cpm. Thus, an appropriate mass conversion factor cannot not be thought of as a single number; it must be selected based on both the sediment location and its condition. For example, dose evaluations of the exposed Par Pond sediment required different mass conversion factors for the doses an individual would receive from inhaling surface dust and plowing up the sediment.

Results

All ^{137}Cs count rates (cpm) were converted to area density ($\mu\text{Ci}/\text{m}^2$) to develop the contour plot of Figure 12. The contour plot smooths the data and uses interpolations between the transects and the pond boundary. This boundary is assumed to have fallout levels of ^{137}Cs , which are effectively negligible relative to the contour analysis. Although the transects shown in Figure 4 are somewhat distant from each other, their ^{137}Cs activity trends did not indicate any unwieldy fluctuations that would invalidate the general trends of the interpolations used in the plot. These assumptions are also supported by 1962 sediment mappings with an underwater G-M detector.³ Overall, the contour map gives the general distribution of the ^{137}Cs in Par Pond, but some "hot points" are removed in the averaging. In particular, for sediment that became exposed, the smoothing did not distinguish the largest individual "hot point" of $25 \mu\text{Ci}/\text{m}^2$ (1440 cpm, transect 3). By contrast, the pond maximum "hot point" of $50 \mu\text{Ci}/\text{m}^2$ (2913 cpm, transect 10) is

distinguished, as other nearby "hot points" serve to define a "hot spot" as opposed to an isolated "hot point". Better map resolution that would reveal more localized ^{137}Cs variations for the entire pond would have required considerably more measurements than the 200 acquired in the present study.

The drawdown exposure of ^{137}Cs was of prime interest in this study. The count-rate data used for the contour plot were averaged for areas contained within 3 meter depth contours. These average count rates were then transformed to $\mu\text{Ci}/\text{m}^2$ and multiplied by their corresponding sediment area (m^2) to yield the ^{137}Cs between the Par Pond depth contours. Successively adding the ^{137}Cs for deeper contours yields the ^{137}Cs exposed as a function of drawdown depth, as summarized in Table 3 and Figure 13. Using the plot, a value of $9.4 \pm 1.5 \text{ Ci}$ of ^{137}Cs is exposed for the drawdown to 181 ft msl. The plot shows that the total inventory is $46.6 \pm 7.2 \text{ Ci}$.

Discussion

The above study was a component of related studies for evaluating the sediment in Par Pond. In particular, the work by SREL on segmented sediment cores of Par Pond has served to provide an independent estimate of the ^{137}Cs pond inventory.⁴ The results, still preliminary, compare favorably with those of the present work, as well as those from the historical predictions, as summarized in Table 4. The present study also updates values given in a recent summary report on cesium isotopes in the SRS environment.¹ These values were based on a less refined analysis of the underwater HPGe measurements,⁷ which had less core data for the average ^{137}Cs depth profile $\bar{P}(z)$ and assumed a constant sediment density profile for $\rho_s(z)$. The updated values also include preliminary results for recent underwater HPGe measurements of Pond C sediments.⁸ Initial publication of the Pond C values⁸ and the refined Par Pond values⁹ occurred after the summary report¹ was issued.

The excellent consistency of the above estimates for ^{137}Cs in Par Pond strongly argue that the

9.4 ± 1.5 Ci for the exposed sediment is a reliable number. This exposed sediment has also been observed with NaI overflight mappings of the area by EG&G/Energy Measurements,¹⁰ but these overflight studies generally provide only relative count rate data for ^{137}Cs . The data may be transformed to $\mu\text{Ci}/\text{m}^2$ by normalizing it to the 9.4 Ci determined for the exposed sediment; comparison with the contour map of Figure 12 will also be useful for this normalization.¹⁰

Various future options for Par Pond are being examined, including further drainage of the pond or refilling it. Decisions on these options may be guided by the results of the present work. The contour map and drawdown plot provide a reasonable overview of the ^{137}Cs distribution in the pond, and "hot point" values may be used for extreme scenarios. Also, the calibration results guide appropriate selection of ^{137}Cs count-rate/activity conversion factors, which differ according to specific dose evaluations.

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Table 1. Gamma-Emitting Radionuclides in Par Pond Sediment and Vegetation

Sediment

Site	^{60}Co (pCi/g)	^{137}Cs (pCi/g)	$^{60}\text{Co}/^{137}\text{Cs}$ (%)
3/East	0.169 ± 0.003	27.00 ± 0.05	0.63 ± 0.01
4/South	0.023 ± 0.001	4.53 ± 0.02	0.52 ± 0.02
5/North	1.100 ± 0.010	74.80 ± 0.10	1.47 ± 0.02
5/South	0.797 ± 0.007	89.70 ± 0.10	0.89 ± 0.01
8-9/South	0.179 ± 0.004	33.90 ± 0.10	0.53 ± 0.01
9/North	0.003 ± 0.001	0.23 ± 0.01	1.46 ± 0.49
10/South	1.310 ± 0.010	136.00 ± 1.00	0.96 ± 0.01
Average	... ^a	... ^a	0.92 ± 0.15^b

Vegetation^c

Site	^{60}Co (pCi/g)	^{137}Cs (pCi/g)	$^{60}\text{Co}/^{137}\text{Cs}$ (%)
2/East	0.38 ± 0.34	35.7 ± 1.6	1.1 ± 1.0
2/West	0.60 ± 0.40	104.0 ± 3.0	0.6 ± 0.4
3/West	0.55 ± 0.43	41.8 ± 2.1	1.3 ± 1.0
4/North	0.50 ± 0.71	144.0 ± 5.0	0.3 ± 0.5
4/South	0.19 ± 0.13	4.5 ± 0.3	4.2 ± 2.9
8/North	0.02 ± 0.12	18.5 ± 0.6	0.1 ± 0.7
8/South	0.49 ± 0.31	48.2 ± 1.6	1.0 ± 0.7
Average	... ^a	... ^a	1.2 ± 0.5^d

^a Average omitted as its interpretation is ill-defined.

^b Average and standard deviation of average. For comparison, weighted average is 0.78%.

^c Activities per ashed sample weights (4-9 g).

^d Average and standard deviation of average. For comparison, weighted average is 0.6%.

Table 2. A/R (pCi/kg/cpm) ¹³⁷Cs Conversion Factors for Par Pond Sediment

Depth	Sediment at Specific Depth (Differential Analysis)					Sediment to Specific Depth (Integral Analysis)				
	$\bar{P}(z)$	Density		A/R		$\bar{P}(z)$	Density		A/R	
	(cm)	(g/cm ³)		(pCi/kg/cpm)			(g/cm ²)		(pCi/kg/cpm)	
		wet	dry	wet	dry		wet	dry	wet	dry
0-1	0.075	0.83	0.28	154	456	0.075	0.83	0.28	154	456
1-2	0.090	1.10	0.47	139	326	0.164	1.93	0.75	145	374
2-3	0.079	1.14	0.53	118	253	0.243	3.07	1.28	135	324
3-4	0.089	1.27	0.66	119	230	0.332	4.34	1.94	131	292
4-5	0.103	1.36	0.78	130	226	0.345	5.70	2.72	130	273
5-6	0.102	1.44	0.88	121	199	0.537	7.14	3.60	129	255
6-7	0.097	1.42	0.97	116	170	0.634	8.56	4.57	126	237
7-8	0.081	1.50	0.98	93	142	0.715	10.06	5.55	121	220
8-9	0.062	1.53	1.03	70	103	0.778	11.59	6.58	115	202
9-10	0.053	1.60	1.11	57	82	0.831	13.19	7.69	108	184
10-11	0.048	1.45	1.11	56	73	0.878	14.64	8.80	102	170
11-12	0.023	1.77	1.27	22	31	0.901	16.41	10.07	94	153
12-13	0.016	1.77	1.28	16	22	0.918	18.18	11.35	86	138
13-14	0.013	1.79	1.30	12	17	0.931	19.97	12.65	80	126
14-15	0.008	1.74	1.28	8	10	0.938	21.71	13.93	74	115
15-16	0.008	1.73	1.30	8	11	0.946	23.44	15.23	69	106
16-17	0.008	1.78	1.37	7	9	0.954	25.22	16.60	65	98
17-18	0.005	1.81	1.44	5	6	0.595	27.03	18.04	61	91
18-19	0.005	1.73	1.36	5	6	0.964	28.76	19.40	57	85
19-20	0.004	1.92	1.56	4	4	0.968	30.68	20.96	54	79
20-21	0.007	1.92	1.44	6	8	0.975	32.60	22.40	51	74
21-22	0.013	1.93	1.44	12	16	0.988	34.53	23.84	49	71
22-23	0.006	2.13	1.76	5	6	0.994	36.66	25.60	46	66
23-24	0.001	1.65	1.38	1	1	0.995	38.31	26.98	44	63
24-25	0.002	1.94	1.66	1	2	0.996	40.25	28.64	42	59
25-26	0.001	1.80	1.49	1	1	0.998	42.05	30.13	41	57
26-27	0.001	1.76	1.55	1	1	0.998	43.81	31.68	39	54
27-28	0.000	1.82	1.62			0.998	45.63	33.30	37	51
28-29	0.000	2.02	1.79			0.999	47.65	35.09	36	49
29-30	0.000	2.05	1.85			0.999	49.70	36.94	34	46
30-31	0.000	1.82	1.63			0.999	51.52	38.57	33	44
31-32	0.000	1.89	1.69			0.999	53.41	40.26	32	42
32-33	0.000	1.91	1.68			0.999	55.32	41.94	31	41
33-34	0.000	1.77	1.70			0.999	57.09	43.64	30	39
34-35	0.000	1.82	1.76			1.000	58.91	45.40	29	38
35-36	0.000	2.01	1.94			1.000	60.92	47.34	28	36
36-37	0.000	2.06	1.98			1.000	62.98	49.32	27	35
37-38	0.000	1.82	1.76			1.000	64.80	51.08	26	33

Note: average profiles for density and $\bar{P}(z)$ from data provided by F.C. Whicker et al, SREL (ref 4)

Table 3. Par Pond ¹³⁷Cs Inventory Analysis

Depth Range		Area ^a	¹³⁷ Cs		
(m)	(ft)	(hectare) ^b	(avg cpm)	(Ci) ^c	(Accum Ci)
0-3	0.0-9.8	317.29	60.8	3.29	3.29
3-6	9.8-19.7	226.66	169.6	6.57	9.86
6-9	19.7-29.5	219.52	387.7	14.53	24.39
9-12	29.5-39.4	166.78	395.1	11.30	35.70
12-15	39.4-49.2	85.15	436.8	7.19	42.84
15-18	49.2-59.1	41.11	534.2	4.59	46.59

^a Data from J.E. Pinder, SREL.

^b hectare = 10⁴ m²

^c A/R = 0.0171 ± 0.0027 μCi/m²/cpm

Estimated Cases for ¹³⁷Cs in Sediment
(Errors dominated by A/R error)

<u>Case</u>	<u>Depth Range</u> (ft)	¹³⁷ Cs (Ci)
Sediment exposed in drawdown to 181 ft msl	0.0-19.0	9.40 ± 1.46
Sediment inventory of entire pond	0.0-59.1	46.59 ± 7.24

Table 4. Comparison of ^{137}Cs Estimates for Sediments of Lower Three Runs System

<u>Location</u>	<u>^{137}Cs Estimates for Sediments^a</u>				
	<u>History</u>	<u>Prediction^b</u>	<u>Cs Report^c</u>	<u>SREL</u>	<u>Present</u>
Pond B	<u>12.0</u>	<u>12.0</u>	<u>12.0</u>	<u>12.0*</u>	<u>12.0</u>
Pond C	-	2-7	2.4	<u>~3.5</u>	<u>~3.9</u>
Par Pond	-	35-59	<u>~42.8</u>	<u>~44.0</u>	<u>46.6</u>
Lower Three Runs Areas	-	5-34	25.8	23.5	20.5
Total	83.0*	83.0	83.0	83.0	83.0

^a Underlined entries are based on pond measurements; the "*" denotes preliminary estimates based on pond measurements. Other entries depend on historical data. For entries with identical values, the one denoted "*" identifies the estimate from which it originated.

^b The predicted ranges result as follows: due to its large area Par Pond is estimated to contain at least 35 Ci of a possible 71 Ci; however, Pond C and Lower Three Runs are estimated to have at least as much as the 12 Ci of Pond B, so that the upper limit for Par Pond is 59 Ci. Assuming, Pond C is similar to Par Pond, it would have at least 2 Ci based on pond area ratios; if similar to Pond B, a value of 12 Ci is estimated. However, because Pond C is closer to Par Pond than Pond B, the average a value of $(12+2)/2 = 7$ Ci is given as an upper limit. If 7 Ci were in Pond C, the minimum in Lower Three Runs is calculated as $71-59-7 = 5$ Ci; similarly, the maximum is calculated as $71-35-2 = 34$ Ci.

^c See reference 1.

Figure 1. Aerial view of Par Pond, 10:25 AM, 21 August 1991.

Figure 2. Pontoon Boat equipped with HPGe Detector, associated electronics, and a hoist for lowering the detector into sampling position.

Figure 3. Detector assembly unit with HPGe Detector Probe and Liquid Nitrogen Dewar.

93X1494.15.AIL

Figure 4. Measurement of ^{137}Cs Countrate for Transects.

93X1494.18.AIL

93X1494.17.AIL

Figure 5. Underwater HPGe Gamma Spectra of Sediment Measured for (a) Hottest Point in the Pond and (b) Hottest Point in the Uncovered Sediment.

93X1494.20.AIL

M83X1494.05.AIL

Figure 6. Transect 1 Measurements of (a) ^{137}Cs and (b) Pond Depth.

93X1494.16.AIL

Figure 7. ^{137}Cs Measurements for Transects 1-9 and their Smoothed Averages as a Function of Pond Depth.

Figure 8. Smoothed Averages of (a) Vegetation and (b) Sediment Temperature as Function of Pond Depth.

93X1494.19.AIL

Figure 9. Low-Level HPGe Spectra for (a) Sediment and (b) Vegetation.

M93X1494.08.AIL

Figure 11. Average Sediment Depth Dependence of (a) ^{137}Cs Probability and (b) Sediment Density.

Figure 12. Contour Map of ^{137}Cs Distribution in Par Pond.

Figure 13. ^{137}Cs in Sediment exposed as a function of drawdown depth (see Table 3).

Appendix A. Raw Data - Underwater HPGe Measurements

The raw data for the underwater HPGe measurements of Par Pond are summarized in Table A.1. Following the notations of Figure 4, all data are categorized according to their transects, and corresponding half-transects are identified according to the general compass directions of their associated shores.

The table gives the position coordinates of each measurement in terms of latitude, longitude, and pond depth. The latitudes and longitudes are approximate, as they are primarily based on visualization of landmarks that could be identified from maps. However, a Magellan GPS unit was available to benchmark some of positions, including those associated with characterizing the "hot spot" of transect #10. The general positioning is estimated to be ± 0.03 min (± 50 m) for both latitude and longitude; however, relative positions along a given transect could be pin-pointed to about ± 0.01 min (± 15 m) using the pond depth measurements and contour maps, as was done in generating the ^{137}Cs map of Figure 12. The table gives the depths in units of feet relative to mean sea level or "ft msl". Par Pond at full pool is at 200 ft msl; thus, actual pond depths at full pool are 200 ft minus the tabulated depth.

The underwater HPGe count rate of the 662 keV gamma peak of ^{137}Cs is that observed in one minute of counting. The counting dates for the data range from 7/11/91 to 11/5/91, which is 117 days; thus, the mid-date of 9/8/91 for this range is within ± 59 days of all measurement dates. Relative to 9/8/91, all the data corrections for ^{137}Cs decay are within $\pm 0.4\%$, which was negligible relative to other errors of the study. Accordingly, the tabulated count rates are not corrected for decay, and a reference date of 9/8/91 is reasonable for comparisons with other ^{137}Cs observations that correspond to significantly remoter dates.

Temperature and vegetation measurements at the bottom depths were taken during the July measurements, before significant drawdown had occurred. These measurements were made for transects 2-9. The tabulated temperatures are self explanatory. For the vegetation observations, a "Y" indicates positive evidence for bottom vegetation, a "Y/N" denotes borderline evidence, and an "N" means no vegetation. The presence of vegetation was determined by visual observation and/or by the patterns on the Lowrance depth finder.

Table A.1. Raw Data - Underwater HPGe Measurements

Transect	Lat 81N (min)	Lon 33W (min)	Depth (ft msl)	Countrate (cpm)	Temp (deg C)	Veg	Data Date
1 West	15.64	32.34	195.3	73 ± 9			7/11/91
	15.65	32.34	192.3	89 ± 9			7/11/91
	15.66	32.33	189.3	167 ± 13			7/11/91
	15.66	32.33	186.3	125 ± 11			7/11/91
	15.67	32.32	183.3	140 ± 12			7/11/91
	15.68	32.32	180.3	233 ± 19			7/11/91
	15.68	32.31	177.3	208 ± 15			7/11/91
	15.69	32.31	174.3	683 ± 29			7/11/91
	15.70	32.30	172.5	622 ± 33			9/19/91
	15.70	32.30	169.5	164 ± 27			9/19/91
	15.71	32.29	167.0	943 ± 30			10/01/91
	15.71	32.29	165.5	930 ± 48			9/19/91
1 East	15.71	32.28	166.5	640 ± 27			9/19/91
	15.72	32.27	169.5	489 ± 33			9/19/91
	15.72	32.26	172.5	84 ± 14			9/19/91
	15.72	32.26	174.3	390 ± 21			7/11/91
	15.72	32.26	177.3	615 ± 29			7/11/91
	15.72	32.26	180.3	632 ± 27			7/11/91
	15.73	32.25	183.3	181 ± 18			7/11/91
	15.73	32.25	186.3	315 ± 22			7/11/91
	15.74	32.24	189.3	63 ± 18			7/11/91
	15.74	32.24	189.3	4 ± 2			7/11/91
	15.74	32.24	192.3	57 ± 8			7/11/91
	15.74	32.23	195.3	48 ± 10			7/11/91
2 West	17.62	31.15	194.3	44 ± 10	28.3	Y	7/17/91
	17.62	31.15	191.3	166 ± 13	28.3	Y	7/17/91
	17.62	31.13	188.3	239 ± 19	28.0	Y	7/17/91
	17.62	31.12	185.3	44 ± 17	26.6	Y/N	7/17/91
2 East	17.62	31.11	185.3	126 ± 16	23.3	N	7/17/91
	17.62	31.11	185.3	136 ± 12	23.3	N	7/17/91
	17.62	31.10	188.3	234 ± 21	26.5	Y/N	7/17/91
	17.62	31.08	191.3	73 ± 9	28.1	Y	7/17/91
	17.62	31.08	194.3	119 ± 16	28.2	Y	7/17/91
3 West	16.87	30.86	194.3	40 ± 6	29.0	Y	7/17/91
	16.87	30.85	191.3	10 ± 3	29.1	Y	7/17/91
	16.87	30.84	188.3	47 ± 7	28.8	Y/N	7/17/91
	16.88	30.84	185.3	17 ± 5	28.7	N	7/17/91
	16.88	30.83	182.3	1440 ± 41	28.5	N	7/17/91
	16.89	30.80	179.3	152 ± 17	26.4	N	7/17/91

Table A.1. (Continued)

Transect	Lat 81N (min)	Lon 33W (min)	Depth (ft msl)	Countrate (cpm)	Temp (deg C)	Veg	Data Date
3 East	16.90	30.79	179.0	272 ± 18	27.6	N	7/18/91
	16.91	30.77	182.0	1388 ± 40	27.2	N	7/18/91
	16.91	30.76	185.0	12 ± 4	28.1	Y	7/18/91
	16.92	30.76	188.0	117 ± 13	28.2	Y	7/18/91
	16.92	30.75	191.0	93 ± 11	28.9	Y	7/18/91
	16.92	30.74	194.0	57 ± 9	28.7	Y	7/18/91
4 North	16.27	30.60	194.5	12 ± 5	29.8	Y	7/16/91
	16.27	30.59	191.5	41 ± 7	29.8	Y	7/16/91
	16.26	30.59	188.5	106 ± 11	29.3	Y	7/16/91
	16.26	30.59	185.5	17 ± 8	29.7	Y	7/16/91
	16.25	30.58	182.5	14 ± 3	29.5	Y	7/16/91
	16.25	30.58	182.5	9 ± 4	26.7	Y	7/16/91
	16.25	30.58	179.5	259 ± 16	24.8	N	7/16/91
	16.25	30.58	176.5	498 ± 29	19.3	N	7/16/91
	16.25	30.57	173.5	409 ± 25	19.7	N	7/16/91
	16.25	30.57	172.3	111 ± 13			9/23/91
	16.24	30.56	169.3	90 ± 14			9/23/91
4 South	16.22	30.54	166.3	370 ± 23			9/23/91
	16.20	30.52	169.3	596 ± 28			9/23/91
	16.19	30.51	172.3	459 ± 28			9/23/91
	16.19	30.51	173.3	290 ± 21	18.3	N	7/16/91
	16.18	30.50	176.3	56 ± 8	19.6	N	7/17/91
	16.18	30.49	179.3	432 ± 24	21.2	N	7/17/91
	16.17	30.48	182.3	599 ± 28	26.1	N	7/17/91
	16.16	30.48	185.3	63 ± 14	28.2	Y	7/17/91
	16.16	30.47	188.3	13 ± 4	28.6	Y	7/17/91
	16.15	30.46	191.3	20 ± 4	28.5	Y	7/17/91
	16.14	30.46	194.3	23 ± 12	28.6	Y	7/17/91
5 North	15.50	31.63	194.5	102 ± 11	28.6	Y	7/16/91
	15.50	31.63	191.5	110 ± 10	28.5	Y	7/16/91
	15.49	31.63	188.5	93 ± 10	28.7	Y	7/16/91
	15.48	31.63	185.5	484 ± 22	29.0	N	7/16/91
	15.47	31.63	182.5	272 ± 22	29.1	N	7/16/91
	15.46	31.63	179.5	579 ± 30	29.2	N	7/16/91
	15.44	31.63	176.5	587 ± 33	19.7	N	7/16/91
	15.41	31.63	173.5	223 ± 24	19.2	N	7/16/91
	15.40	31.64	172.5	181 ± 21			9/19/91
	15.38	31.64	169.5	95 ± 11			9/19/91
	15.37	31.64	166.5	57 ± 20			9/19/91
	15.36	31.64	163.5	1082 ± 40			9/19/91
	15.36	31.64	160.5	529 ± 28			9/19/91
	15.34	31.64	157.5	461 ± 33			9/19/91

Table A.1. (Continued)

Transect	Lat 81N (min)	Lon 33W (min)	Depth (ft msl)	Count rate (cpm)	Temp (deg C)	Veg	Data Date
5 South	15.33	31.64	156.5	352 ± 28			9/19/91
	15.29	31.65	160.5	740 ± 35			9/19/91
	15.28	31.65	163.5	20 ± 4			9/19/91
	15.27	31.65	166.5	623 ± 34			9/19/91
	15.26	31.65	169.5	348 ± 24			9/19/91
	15.26	31.65	172.0	380 ± 20			10/01/91
	15.26	31.65	172.5	365 ± 29			9/19/91
	15.26	31.65	173.5	721 ± 29	20.1	N	7/16/91
	15.25	31.65	176.5	420 ± 33	23.8	N	7/16/91
	15.25	31.65	179.5	397 ± 26	25.0	N	7/16/91
	15.24	31.65	182.5	158 ± 13	28.9	N	7/16/91
	15.24	31.65	182.5	11 ± 3	29.2	N	7/16/91
	15.24	31.65	185.5	292 ± 23	29.2	Y	7/16/91
	15.23	31.65	188.5	85 ± 10	29.4	Y	7/16/91
	15.22	31.65	191.5	95 ± 10	29.1	Y	7/16/91
	15.21	31.65	194.5	33 ± 9	29.5	Y	7/16/91
6 West	14.71	31.57	192.9	20 ± 9	31.2	Y	7/23/91
	14.71	31.55	189.9	97 ± 15	30.5	Y	7/23/91
	14.71	31.53	186.9	26 ± 9	30.1	Y/N	7/23/91
	14.70	31.51	183.9	7 ± 4	29.2	N	7/23/91
	14.70	31.49	180.9	22 ± 13	24.6	N	7/23/91
	14.70	31.47	177.9	12 ± 6	23.4	N	7/23/91
	14.69	31.45	174.9	67 ± 15	20.2	N	7/23/91
	14.69	31.43	172.3	471 ± 23			9/23/91
	14.69	31.43	171.9	505 ± 29	18.6	N	7/23/91
	14.69	31.41	169.3	250 ± 21			9/23/91
	14.68	31.40	166.3	515 ± 27			9/23/91
	14.68	31.38	163.3	175 ± 18			9/23/91
	14.68	31.37	160.3	375 ± 23			9/23/91
	14.68	31.34	157.3	274 ± 17			9/23/91
	14.67	31.31	154.3	197 ± 18			9/23/91
	14.67	31.29	151.3	335 ± 23			9/23/91

Table A.1. (Continued)

Transect	Lat 81N (min)	Lon 33W (min)	Depth (ft msl)	Countrate (cpm)	Temp (deg C)	Veg	Data Date
6 East	14.66	31.21	148.3	634 $\pm$ 32			9/23/91
	14.65	31.16	151.3	1032 $\pm$ 38			9/23/91
	14.65	31.15	154.3	864 $\pm$ 33			9/23/91
	14.65	31.14	157.3	220 $\pm$ 18			9/23/91
	14.65	31.13	160.3	547 $\pm$ 24			9/23/91
	14.65	31.12	163.3	488 $\pm$ 22			9/23/91
	14.65	31.11	166.3	392 $\pm$ 20			9/23/91
	14.64	31.10	169.3	251 $\pm$ 21			9/23/91
	14.64	31.09	171.9	460 $\pm$ 31	18.4	N	7/23/91
	14.64	31.09	172.3	451 $\pm$ 21			9/23/91
	14.64	31.08	174.9	562 $\pm$ 32	20.3	N	7/23/91
	14.64	31.07	177.9	921 $\pm$ 42	24.5	N	7/23/91
	14.64	31.06	180.9	59 $\pm$ 13	27.4	N	7/23/91
	14.64	31.06	183.9	45 $\pm$ 10	28.8	N	7/23/91
	14.64	31.05	186.9	163 $\pm$ 20	29.3	Y	7/23/91
	14.63	31.04	189.9	54 $\pm$ 16	29.7	Y	7/23/91
	14.63	31.03	192.9	13 $\pm$ 6	29.7	Y	7/23/91
7 West	13.99	31.51	194.0	65 $\pm$ 8	28.5	Y	7/18/91
	14.00	31.48	191.0	215 $\pm$ 19	27.7	Y	7/18/91
	14.01	31.45	188.0	310 $\pm$ 21	28.1	Y	7/18/91
	14.02	31.43	185.0	179 $\pm$ 14	27.9	Y/N	7/18/91
	14.03	31.42	182.0	80 $\pm$ 16	26.8	N	7/18/91
	14.04	31.39	179.0	322 $\pm$ 20	22.3	N	7/18/91
	14.05	31.34	176.0	327 $\pm$ 20	21.3	N	7/18/91
	14.07	31.30	173.0	336 $\pm$ 22	18.4	N	7/18/91
	14.07	31.29	172.3	286 $\pm$ 21			9/23/91
	14.09	31.25	169.3	469 $\pm$ 28			9/23/91
	14.10	31.22	166.3	677 $\pm$ 29			9/23/91
	14.11	31.18	163.3	384 $\pm$ 23			9/23/91
	14.12	31.15	160.3	518 $\pm$ 27			9/23/91
	14.12	31.15	157.3	132 $\pm$ 12			9/23/91
	14.13	31.14	154.3	227 $\pm$ 15			9/23/91
	14.13	31.14	151.3	42 $\pm$ 6			9/23/91
	14.14	31.12	148.3	281 $\pm$ 21			9/23/91
	14.15	31.08	145.3	623 $\pm$ 30			9/23/91
	14.16	31.05	142.3	684 $\pm$ 28			9/23/91

Table A.1. (Continued)

Transect	Lat 81N (min)	Lon 33W (min)	Depth (ft msl)	Countrate (cpm)	Temp (deg C)	Veg	Data Date
7 East	14.17	31.01	145.3	470 ± 27			9/23/91
	14.19	30.98	148.3	513 ± 23			9/23/91
	14.19	30.95	151.3	678 ± 26			9/23/91
	14.20	30.93	154.3	390 ± 24			9/23/91
	14.20	30.91	157.3	450 ± 29			9/23/91
	14.21	30.90	160.3	372 ± 24			9/23/91
	14.21	30.89	163.3	262 ± 16			9/23/91
	14.21	30.88	166.3	216 ± 20			9/23/91
	14.22	30.88	169.3	384 ± 24			9/23/91
	14.22	30.87	172.3	632 ± 33			9/23/91
	14.22	30.87	173.0	428 ± 28	18.6	N	7/18/93
	14.22	30.87	176.0	338 ± 26	20.2	N	7/18/93
	14.22	30.86	179.0	701 ± 30	21.2	N	7/18/93
	14.22	30.85	182.0	442 ± 27	26.7	N	7/18/93
	14.22	30.85	185.0	83 ± 9	29.6	Y	7/18/93
	14.23	30.85	188.0	113 ± 11	29.5	Y	7/18/93
	14.23	30.84	191.0	23 ± 9	29.7	Y	7/18/93
	14.23	30.84	194.0	45 ± 7	30.5	Y	7/18/93
8 North	14.46	32.19	194.0	40 ± 7	29.3	Y	7/18/91
	14.45	32.19	191.0	68 ± 9	29.4	Y	7/18/91
	14.44	32.19	188.0	98 ± 15	29.3	Y	7/18/91
	14.43	32.19	185.0	39 ± 7	27.9	N	7/18/91
	14.42	32.19	182.0	115 ± 14	28.2	N	7/18/91
	14.41	32.18	179.0	122 ± 14	25.3	N	7/18/91
	14.39	32.18	176.0	101 ± 13	21.4	N	7/18/91
	14.36	32.18	173.0	92 ± 14	19.9	N	7/18/91
	14.36	32.18	172.3	132 ± 14			9/23/91
	14.33	32.18	169.3	125 ± 15			9/23/91
8 South	14.27	32.17	166.3	600 ± 28			9/23/91
	14.24	32.16	169.3	370 ± 23			9/23/91
	14.22	32.16	172.3	1055 ± 37			9/23/91
	14.21	32.16	173.0	288 ± 17	18.7	N	7/18/91
	14.19	32.16	176.0	229 ± 16	20.5	N	7/18/91
	14.18	32.16	179.0	115 ± 15	21.8	N	7/18/91
	14.17	32.16	182.0	25 ± 5	27.9	N	7/18/91
	14.16	32.16	185.0	122 ± 11	28.0	Y/N	7/18/91
	14.15	32.15	188.0	131 ± 12	28.1	Y	7/18/91
	14.14	32.15	191.0	74 ± 10	28.3	Y	7/18/91
	14.12	32.15	194.0	46 ± 7	28.6	Y	7/18/91

Table A.1. (Continued)

Transect	Lat 81N (min)	Lon 33W (min)	Depth (ft msl)	Countrate (cpm)	Temp (deg C)	Veg	Data Date
9 West	14.71	32.97	194.0	37 ± 6	28.8	Y	7/18/91
	14.72	32.97	191.0	101 ± 11	28.0	Y/N	7/18/91
	14.73	32.94	188.0	119 ± 13	27.8	N	7/18/91
	14.74	32.90	185.0	233 ± 19	28.1	N	7/18/91
	14.76	32.86	182.0	2 ± 1	27.3	N	7/18/91
	14.77	32.82	179.0	823 ± 31	23.5	N	7/18/91
	14.78	32.79	176.0	133 ± 13	22.8	N	7/18/91
9 East	14.78	32.79	176.0	307 ± 19	22.9	N	7/18/91
	14.79	32.76	179.0	841 ± 31	22.5	N	7/18/91
	14.79	32.75	182.0	19 ± 5	26.9	N	7/18/91
	14.80	32.75	185.0	142 ± 14	27.8	Y	7/18/91
	14.80	32.74	188.0	92 ± 13	28.0	Y	7/18/91
	14.80	32.74	191.0	2 ± 2	28.2	Y	7/18/91
	14.80	32.73	194.0	12 ± 3	28.8	Y	7/18/91
10 North South	15.34	31.54	157.0	291 ± 17			11/05/91
	15.33	31.53	154.0	834 ± 36			11/05/91
	15.29	31.53	155.0	1664 ± 49			11/05/91
	15.28	31.53	154.0	1568 ± 46			11/05/91
	15.28	31.53	154.0	2397 ± 58			11/05/91
	15.28	31.54	155.0	2913 ± 66			11/05/91
	15.28	31.51	154.0	1226 ± 42			11/05/91
	15.27	31.53	156.0	731 ± 33			11/05/91
	15.26	31.53	157.0	785 ± 32			11/05/91
	15.24	31.53	160.0	808 ± 34			11/05/91
	15.23	31.54	166.0	748 ± 33			11/05/91

Appendix B. Analysis of Vegetation and Temperature at Pond Bottom

The data for vegetation and temperature measurements are given in Table A.1. These measurements were made for transects 2-9 and are averaged as a function of bottom depth in Figure 8. The temperature measurements were made with a thermocouple reading thermometer, the sensor of which was attached to the lower screening shield of the detector. The presence of vegetation was determined by visual observation and/or by the patterns on the Lowrance depth finder.

The smoothed data plotted in Figure 8 was obtained using the unsmoothed raw data, as plotted in Figure B.1. The temperature plot is self-explanatory.

The vegetation plot uses a value of 1.0 for observed vegetation (Y in Table A.1), 0.5 for borderline vegetation (Y/N), and 0.0 for no vegetation (N). This numerical treatment essentially treats the data as probabilities for observing vegetation. The numerical data of Figure B.1 were smoothed by point averaging. Each resulting averaged value in Figure 8 uses the 19 points from Figure B.1, including a single point and adjacent 18 points (9 above and 9 below) at monotonic depths. Corresponding smoothed average depths are assigned to each smoothed vegetation and temperature value.

Figure B-1. All Transect Measurements of (a) Vegetation and (b) Sediment Temperature.

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Appendix C. Underwater HPGe Calibration Studies

Calculations of the underwater HPGe ^{137}Cs calibration yield A/R in units of pCi/m²/cpm from the expression

$$R = A \int_0^h \int_0^a P(z) I_\gamma \epsilon(r, z) 2\pi r dr dz,$$

which is identical to Eq. 3 of the main text except that $\bar{P}(z)$ has been replaced by $P(z)$. The text defines $\epsilon(r, z)$ and other parameters relative to Eqs. 1-3. The BASIC code EFFUGDBD was developed for the calculations; it also produces A/R in units of pCi/kg/cpm and pCi/m³/cpm for comparison. The code listing and an example run are given in Figure C.1.

Calculations for A/R are given in Table C.1, and are based on data given in the code listing and example. Using the notations of Eqs. 1-3 and Figure 10 of the main text, code parameters used are:

Manual Inputs

z_0	= detector center to sediment surface (in) = 5
z_D	= detector can radius (in) = 1.5
$\epsilon_A(0,0)$	= unattenuated efficiency at sediment = 0.00294
s_w	= attenuation coefficient of water (cm ²) = 0.085
p_w	= density of water (g/cm ³) = 1
s_s	= attenuation coefficient of sediment (cm ² /g) = 0.085
a	= radial integral max R (cm) = 70
dr	= radial integral step DR (cm) = 2
h	= axial integral max Z (cm) = core depth ≤ 38
dz	= axial integral step DZ (cm) = 1

Data within code

I_γ	= fraction of 662 keV gammas per ^{137}Cs decay = 0.8521
dpm/pCi	= conversion factor = 0.037 x 60 = 2.22

Data in files

$p_s(z)$	= density of sediment between core levels z and $z+1$
$P(z)$	= probability of ^{137}Cs between core levels z and $z+1$ per code normalization of raw data.

The input $\epsilon_A(0,0) = 0.002984$ was determined by counting an effective point-source ^{137}Cs standard directly under the bottom screen of the detector while in air.

The calculations of Table C.1 yield an average A/R of 17068 pCi/m²/cpm for Par Pond sediment. Pending availability of additional core samples from SREL, the accuracy of A/R may be improved in the future. The table also includes test calculations showing that the integration mesh ($dr=2, dz=1$) and volume size are sufficiently accurate for the calculations. The volume is cylindrical with radius $a = 70$ cm and $h \leq 38$ cm for the individual the core samples. Because all core samples extended to depths where ^{137}Cs had decreased to negligible levels, it is assumed that all ^{137}Cs is contained within a cylinder of $h = 38$ cm. The choice of volume radius $a = 70$ cm was tested for a uniform $p_s(z) = 1.5$ g/cm³ and uniform $P(z) = 1/38$ cm⁻¹ by comparing A/R calculations for $a = 50, 70$, and 100 cm. Differences between the resulting A/R in Table C.1 are very small, implying that an $a = 70$ cm produces A/R to within less than 1% uncertainty. The difference in using a 1 cm or 2 cm mesh in the integration is also shown to be 0.2% for similar examples given in the table. Thus, the code integrations were quite adequate for yielding A/R for Par Pond sediment.

During the process of developing the A/R calculations, interest arose concerning the type of factor that is most appropriate for a given application. A calculational study was performed for uniform ^{137}Cs in sediment contained within a variety of sediment depths. The resulting A/R in nCi/m²/cpm and pCi/kg/cpm units are plotted as a function of h in Figure C.2. Here, the nCi/m²/cpm value is relatively constant for low h but increases rapidly for larger h . By contrast, the nCi/kg/cpm value is relatively constant for large h , but increases rapidly with

lower h . From Figure 11, it is clear that most of the Par Pond ^{137}Cs is distributed at shallow

depths or low h , and thus an A/R in $\text{nCi/m}^2/\text{cpm}$ units is most appropriate.

Table C.1. Calculations of A/R

Sediment Core Measurements^a

$P(z)$ and $p_s(z)$ data in code listing (Figure C.1) $a = 70$ cm, $dr = 2$ cm, $h =$ (below), $dz = 1$ cm

Core		h (cm)	A/R ($\text{pCi/m}^2/\text{cpm}$)
1	CP-17	23	14119
2	CP-23	34	44005
3	CP-9	26	13419
4	CP-33	25	16684
5	CP-37	38	14802
6	CP-49	22	16552
7	CP-48/50	16	17452
8	CP-30	20	11244
9	CP-46	25	8697
10	CP-47	26	16441
11	CP-45	13	9893
12	CP-59	19	21632

Average^b 17078 ± 2654^c

^a Core data including labels from F.W. Whicker group, SREL.

^b Text expresses as $0.0171 \pm 0.0027 \mu\text{Ci/m}^2/\text{cpm}$.

^c Error is standard deviation of mean.

Calculation Tests for Sensitivity

Sensitivity parameters	$p_s(z)$ (g/cm^3)	a (cm)	dr (cm)	h (cm)	dz (cm)	A/Z ($\text{pCi/m}^2/\text{cpm}$) (rel)
a	1.5	50	2	38	1	47204 1.013
	constant	70	2	38	1	46578 $\equiv$ 1.000
		100	2	38	1	46495 0.998
dr, dz	1.1	50	1	50	1	46090 $\equiv$ 1.000
	constant	50	2	50	2	46200 1.002
dz	1.1	70	2	10	1	12441 $\equiv$ 1.000
	constant	70	2	10	2	12464 1.002

Figure C.1 EFFUGDPD Code listing and example.

Code Listing

```

10 REM a:EFFUGDPD.BAS
11 DIM DS(50),DSZ(50)
12 SUMD=0
13 FOR I=0 TO 37
14 READ DS(I):SUMD = SUMD+DS(I)
15 DSZ(I)=SUMD/(I+1)
16 REM PRINT I, DS(I),DSZ(I)
17 NEXT I
20 DIM P(50)
21 READ PTOT
22 N = 0
23 READ P(N):P(N)=P(N)/PTOT
24 IF P(N)*PTOT => -1 THEN N=N+1:GOTO 23
25 SUM=0
26 FOR I=0 TO N-1
27 P(I)=N*P(I)
30 SUM = P(I)+SUM
35 NEXT I
40 PRINT SUM
100 REM inputs
110 INPUT"Z0 = detector center to sediment surface(in)";Z0:Z0=2.54*Z0
115 INPUT"ZR = detector can radius(in)";ZR:ZR=2.54*ZR
120 INPUT"E00 = unattenuated detector efficiency at sediment";E00
125 INPUT"DW = density of water (g/cm3)";DW
130 INPUT"UW = attenuation coefficient of water (cm2/g)";UW:UW=DW*UW
135 PRINT"DS = density of sediment (g/cm3) - input vs z files";REM ds/line180
140 INPUT"US = attenuation coefficient of sediment (cm2/g)";US
150 REM F = 661 gamma emission rate/pCi Cs-137 (gpm/pCi)
151 F = .8521*.037*60
160 INPUT"Radial integral max R (cm)";LR
165 INPUT"Radial integral step DR (cm)";DR
170 INPUT"Axial integral max Z (cm)";LZ
175 INPUT"Axial integral step DZ (cm)";DZ
180 DS=DSZ(LZ-1)
200 REM calc
210 FOR Z = .5*DZ TO LZ-.5*DZ STEP DZ
225 INTR = 0
230 FOR R = .5*DR TO LR-.5*DR STEP DR
235 SECO = SQR((Z+Z0)^2+R^2)/(Z0+Z)
237 PZ = P(INT(Z))
238 USZ=US*DSZ(INT(Z))
240 INTR = INTR + PZ * (Z0^2/((Z0+Z)^2+R^2)) * EXP(-UW*(Z0*SECO-ZR)-USZ*Z*SECO)
* R*DR
250 NEXT R
260 INTRZ = INTRZ + INTR*DZ
270 NEXT Z
300 REM results
310 CPCIG = F*DS*2*3.14159*E00*INTRZ
315 PRINT" pCi/m3 per UW cpm = "; 1000000!/(CPCIG/DS)
320 PRINT" pCi/kg per UW cpm = "; 1000/CPCIG
325 PRINT" pCi/m2 per UW cpm = "; (LZ/100)*1000000!/(CPCIG/DS)
800 END

```

Example CP-59

```

RUN
19
Z0 = detector center to sediment surface(in)? 5
ZR = detector can radius(in)? 1.5
E00 = unattenuated detector efficiency at sediment? .002984
DW = density of water (g/cm3)? 1
UW = attenuation coefficient of water (cm2/g)? .085
DS = density of sediment (g/cm3) - input vs z files
US = attenuation coefficient of sediment (cm2/g)? .085
Radial integral max R (cm)? 70
Radial integral step DR (cm)? 2
Axial integral max Z (cm)? 19
Axial integral step DZ (cm)? 1
pCi/m3 per UW cpm = 113854.8
pCi/kg per UW cpm = 75.21701
pCi/m2 per UW cpm = 21632.41
ok

```

Figure C.1 EFFUGDPD Code listing and example. (Continued)

Density

```

900 REM densities per ht 0-1, 1-2, .... 37-38
910 DATA 0.83,1.10,1.14,1.27,1.36,1.44,1.42,1.50,1.53,1.60
920 DATA 1.45,1.77,1.77,1.79,1.74,1.73,1.78,1.81,1.73,1.92
930 DATA 1.92,1.93,2.13,1.65,1.94,1.80,1.76,1.82,2.02,2.05
940 DATA 1.82,1.89,1.91,1.77,1.82,2.01,2.06,1.82

```

¹³⁷Cesium Probability

Data Sets

1000 REM ptot	
1010 REM DATA 63.41	
1100 REM p(i)	
1110 REM DATA 4.37,7.56,5.29,5.53,5.94,4.95,8.53,3.76,3.70,3.10	CP-17
1120 REM DATA 4.05,1.25,1.46,0.74,0.04,0.36,0.71,-0.10,0.79,0.10	
1130 REM DATA 0.39,0.71,0.22,-100	
1140 REM DATA 0.0,0.17,0.39,0.62,-100	
2000 REM ptot	
2010 REM DATA 655.19	
2100 REM p(i)	
2110 REM DATA 1.2,2.0,4.2,2.8,2.3,3.6,6.6,24.4,82.9,112.1	CP-23
2120 REM DATA 123.9,24.3,9.4,8.6,8.9,9.0,8.3,8.0,9.4,13.2	
2130 REM DATA 41.3,90.3,37.5,3.88,6.37,5.57,3.25,0.63,0.14,0.0	
2140 REM DATA 0.0,0.17,0.39,0.62,-100	
3000 REM ptot	
3010 REM DATA 263.6	
3100 REM p(i)	
3110 REM DATA 15,13.6,19.4,26.2,66.7,62.6,20.3,9.4,5.0,3.2	CP-9
3120 REM DATA 2.6,2.8,1.3,1.1,2.2,3.8,3.0,1.2,.9,.8	
3130 REM DATA .6,.7,0,.3,0,.9,-100	
3140 REM DATA rem 0.0,0.17,0.39,0.62,-100	
4000 REM ptot	
4010 REM DATA 172.66	
4100 REM p(i)	
4110 REM DATA 4.41,4.82,6.54,13.25,18.77,27.09,30.08,28.46,13.78,8.05	CP-33
4120 REM DATA 4.88,2.56,1.58,1.41,.56,.78,1.0,1.09,.82,1.12,.37,.49	
4130 REM DATA .62,.06,.07,-100	
5000 REM ptot	
5010 REM DATA 142.24	
5100 REM p(i)	
5110 REM DATA 7.44,7.89,6.74,17.21,25.87,18.71,14.34,11.13,8.01,5.59	CP-37
5120 REM DATA 4.01,3.42,2.09,1.72,0.79,1.16,0.26,0.24,0.09,0.55,0.08	
5130 REM DATA 0.17,0.27,0.26,0.57,0.67,0.32,-0.39,0.79,0.03,0.63	
5140 REM DATA 0.22,0.32,0.17,0.82,-0.19,-0.02,0.26,-100	
6000 REM ptot	
6010 REM DATA 454.70	
6100 REM p(i)	
6110 REM DATA 21.37,24.14,37.55,37.89,35.36,47.85,48.62,46.64,30.41,16.25	CP-49
6120 REM DATA 11.26,10.01,17.06,26.75,13.07,8.91,6.86,4.59,3.67,3.83	
6130 REM DATA 1.87,0.73,-100	
7010 REM DATA 420.21	
7100 REM p(i)	
7110 REM DATA 18.20,21.47,22.82,26.43,22.72,27.21,37.59,61.44,59.83,48.40	CP-48/50
7120 REM DATA 40.51,18.53,9.60,4.12,1.00,0.35,-100	
8010 REM DATA 59.75	
8100 REM p(i)	
8110 REM DATA 5.49,12.25,9.54,8.17,6.25,3.72,3.95,2.78,1.20,1.00	CP-30
8120 REM DATA 1.26,0.81,0.26,0.08,0.50,0.43,0.72,0.73,0.54,0.07,-100	
9010 REM DATA 981.51	
9100 REM p(i)	
9110 REM DATA 325.85,249.29,149.96,113.12,60.50,26.76,19.45,10.60,6.07,3.81	CP-46
9120 REM DATA 1.89,2.06,2.68,1.46,1.00,1.17,1.14,0.86,0.43,0.47	
9130 REM DATA 1.06,0.31,0.54,0.13,0.43,-100	
10010 REM DATA 1889.96	
10100 REM p(i)	
10110 REM DATA 2.87,3.52,65.00,225.59,285.49,432.89,371.73,174.99,112.88,52.99	CP-47
10120 REM DATA 20.58,19.06,19.00,19.08,15.63,14.18,10.66,9.32,8.52,7.59	
10130 REM DATA 5.91,4.96,2.47,2.78,1.32,0.96,-100	
11010 REM DATA 49.43	
11100 REM p(i)	
11110 REM DATA 7.89,11.52,9.33,6.58,5.27,2.33,2.08,1.66,0.69,0.36,0.48,0.63,0.61	CP-45
11120 REM DATA -100	
12010 DATA 1312.01	
12100 REM p(i)	
12110 DATA 20.75,26.02,27.74,35.06,54.89,110.43,184.53,223.12,128.84,147.15	CP-59
12120 DATA 115.96,87.41,51.02,33.99,15.95,17.50,18.18,8.11,5.36,-100

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Figure C-2. A/R Conversion Factors of Uniform ^{137}Cs and Sediment as a Function of ^{137}Cs Depth (h).

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