

# PLUTONIUM IN THE AQUATIC ENVIRONMENT Its behaviour, distribution and significance

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## Abstract

### PLUTONIUM IN THE AQUATIC ENVIRONMENT - ITS BEHAVIOUR, DISTRIBUTION AND SIGNIFICANCE

The source of plutonium contamination in the environment is discussed. The fall-out levels of plutonium in seaweeds, rainwater, soils and aquatic surface sediments from the Bombay region were measured by radiochemical separation using <sup>239</sup>Pu as an internal tracer and alpha spectrometry.

The behaviour of trace amounts of plutonium discharged from fuel reprocessing operations into the aquatic environment of Bombay Harbour Bay was investigated in detail and the distribution of this radionuclide in different matrices of the marine environment - seawater, silt, sediments, organisms and sea salt - were studied. The suspended silt and bottom sediments of coastal waters have been found to have a high capacity for removal of plutonium from seawater. Nearly 100% of the plutonium gets removed by sediments from silt-laden coastal water. The preferential uptake of plutonium by benthic organisms was observed.

The interaction of plutonium solutions and trace plutonium present in the fuel reprocessing effluents with sea salt were studied and the formation of both ionic and non-ionic species of plutonium were investigated. Organic matter added to seawater was found to inhibit hydrolysis and precipitation of added Pu and the anionic species formed increased with time. The extraction of organic matter from coastal sediments contaminated with plutonium showed the presence of the element in the purified organic fraction.

The average concentration of Pu in benthic organisms from the discharge locale is only 0.01% of the limiting values. Biological uptake and transport of Pu might be insignificant in coastal areas, sediment being the major depository of all released Pu. Needs further study to understand its biological and geochemical significance.

## INTRODUCTION

Naturally occurring plutonium produced as a result of neutron absorption of <sup>238</sup>U has been detected in ultra trace quantities in uranium-rich minerals only. The presence of this element in nature essentially results from human activities. Plutonium has entered the human environment as a consequence of (a) nuclear weapon testing, (b) accidental releases, and (c) effluent discharges from plutonium-handling and processing facilities.

## SOURCES OF PLUTONIUM CONTAMINATION

Subsequent to the atomic tests conducted since 1945 plutonium appeared in global fall-out. In nuclear explosions plutonium isotopes can be formed by neutron capture of uranium atoms or by the escape of fissile nuclides

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that have not undergone fission. Plutonium isotopes 238, 239, 240, 241, 242 and 244 were detected in the airborne debris of the first large-scale thermo-nuclear explosion [1], the predominant one being  $^{239}\text{Pu}$ .

It has been estimated that nearly 325 kilocuries of  $^{239}\text{Pu}$  and about 8 kilocuries of  $^{240}\text{Pu}$  have been deposited as a result of global fall-out from weapon testing [2]. On a weight basis, the deposited plutonium has been calculated to be about 5300 kg (compared to about 300 kg of  $^{90}\text{Sr} - ^{137}\text{Cs}$ ). Thus there is already a large inventory of plutonium in the environment from this source.

Many instances of accidental release of plutonium into the environment have taken place. The SNAP failure [2] resulted in the release of 1 kg of  $^{238}\text{Pu}$  (17 kCi). It is significant that this single incident involved the deposition of more  $^{238}\text{Pu}$  (more than double) than that deposited from weapon testing.

Effluent discharges from irradiated-fuel reprocessing and plutonium-handling facilities can lead to 'above background' levels in local environments [3,4]. In a study conducted by ENEA it was reported that about 98.5 to 99% of the total plutonium contained in the irradiated fuel elements are generally recovered, the remaining 1 to 1.5% being discharged to waste [5]. However, since most of the fission product activity is contained it was felt that releases to the environment through the effluents might be small. It has been reported recently that the total amount of Pu discharged from Windscale during the last 15 years is approximately  $10^4$  Ci [4] and probably about 0.3% of the plutonium produced in the UK is released into the sea [6].

#### ENVIRONMENTAL PLUTONIUM

Unlike  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ , plutonium in the environment has not been studied extensively. Its study is unique in that this artificial element has no stable counterpart, unlike the fall-out radionuclides studied extensively. Studies by Krey et al. [7] on human tissues revealed the increase in environmental concentration of  $^{239}\text{Pu}$ . Inhalation is considered the major pathway of plutonium intake. As a result, no emphasis has been placed on distribution studies of Pu in the environment.

Since oceans cover 70% of the area of the earth, they receive a larger share of the fall-out radionuclides. In addition, rivers also carry land-washed fall-out into the ocean. Fuel-reprocessing facilities are normally located near water bodies or most often low-level liquid effluents released from them find their way to the aquatic environment. Thus, as the major recipient of released plutonium, the study of behaviour and distribution of this element in different matrices of the aquatic environment assumes importance.

Barring a few measurements of plutonium concentration in some biological specimens [8,9], no systematic study of fall-out levels of plutonium in the aquatic environment was reported till 1964. The measurements of fall-out levels of plutonium in Pacific coastal waters revealed the high plutonium-accumulating capacity of certain marine organisms [10]. High trophic-level organisms like fish indicated low accumulation factors. The high concentrating ability of marine plants was used to detect and estimate  $^{238}\text{Pu}$  in the marine environment.

The paper deals with investigations carried out to obtain estimates of fall-out levels of plutonium in the Bombay region its distribution in the aquatic environment of Bombay Harbour Bay and to study the behaviour of trace quantities of plutonium in seawater and sediments

Methodology for plutonium estimation in environmental samples

The methodology used for the estimation of transuranics especially plutonium, in marine environmental samples has been reviewed elsewhere [11] Unlike other radionuclides estimated in environmental samples plutonium estimation cannot be based on any chemical yield obtained and therefore it is now an accepted practice to use an internal tracer for the determination of plutonium <sup>239</sup>Pu has been used as a tracer in this work The radiochemically isolated Pu is electroplated and is estimated by alpha-spectrometry, using solid-state detectors and a 100,512-channel analyser Since the peaks of <sup>239</sup>Pu and <sup>240</sup>Pu cannot be resolved, all the values given for <sup>239</sup>Pu in the paper represent the activity of both isotopes 239 and 240 In some cases <sup>238</sup>Pu has also been estimated

To ensure reliable results reagent blanks were carried out periodically Some interlaboratory comparisons were also undertaken with the International Laboratory of Marine Radioactivity, Monaco, and Woods Hole Oceanographic Institution USA (Dr V T Bowen)

Fall-out levels of plutonium in the Bombay Region

To assess the impact of trace quantities of plutonium released to the aquatic environment it is necessary to know the background levels of Pu in the region Therefore estimates of fall-out levels of plutonium in some matrices of the environment were undertaken

The fall-out levels of plutonium in the western coastal waters of India were estimated by measurement of plutonium levels in seaweed samples Seaweeds are known to have a high accumulating capacity for plutonium [10] The plutonium levels in seaweeds obtained from two locations on the West Coast during different periods are given in Table I The relatively high levels of plutonium obtained in seaweeds collected during 1971 from Tarapur can only be explained by the possible higher age of the species collected and/or by the offshore location of these species, thereby reflecting the higher levels of Pu in offshore waters Such higher concentrations have been reported in the offshore waters of the Pacific Ocean [12] The levels are comparable with those obtained in samples from the Pacific and Atlantic Oceans Assuming a concentration factor of 1000 for seaweeds for plutonium, the concentration of coastal waters calculates to 10<sup>-4</sup> to 10<sup>-3</sup> pCi/l.

To obtain estimates of fall-out plutonium in precipitation in the Bombay region, rainfall samples were collected for two years from June to September at Trombay The samples were kept acidified to inhibit sorption on collection bottles The collected samples were processed after the addition of <sup>236</sup>Pu tracer The results obtained are given in Table II The measurements of fall-out deposition at Bombay have shown that 80-90% of annual deposition of <sup>90</sup>Sr takes place during the rainy season [13] Therefore these values from rainfall give rough estimates of the annual plutonium deposition.

isotopes 238, 239, 240 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000

plutonium into the environment during the release of 1 kg of plutonium. The single incident involved the plutonium that deposited from weapon

reprocessing and plutonium-handling levels in local environment was reported that about 5% of the irradiated fuel elements discharged to the product activity is contained, through the effluents might be the total amount of Pu discharged is approximately 10<sup>4</sup> Ci [4] and in the UK is released into

environment has not been studied. The fissionable element has no stable isotopes. It has been studied extensively. Studies have shown a steady increase in environmental levels. The major pathway of plutonium has been placed on distribution

earth, they receive a larger amount. Rivers also carry land-based plutonium. Releasing facilities are normally located near liquid effluents released from nuclear power plants. Thus, as the major pathway of plutonium and its behaviour and distribution in the environment assumes

concentration in some areas. The fall-out levels of plutonium were measured till 1964. The measurements in coastal waters revealed that plutonium in certain marine organisms [10] has low accumulation factors. The alpha-spectrometry was used to detect and

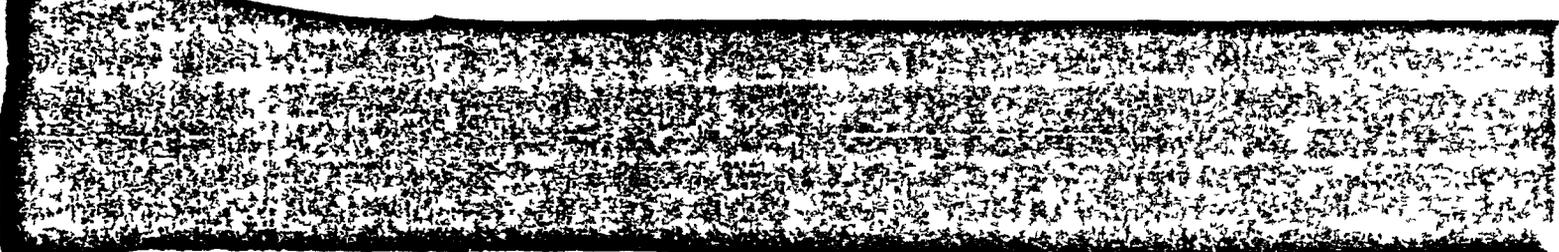


TABLE I  $^{239}\text{Pu}$  LEVELS IN SEaweEDS COLLECTED FROM COASTAL WATERS (ARABIAN SEA) OF INDIA

Date of collection	Location	Species	$^{239}\text{Pu}$ (dpm/g dry wt)
May 1966	Tarapur $19^{\circ} 54' \text{N}$ $72^{\circ} 41' \text{E}$ <sup>a</sup>	<i>Sargassum</i>	$0.21 \pm 0.07$
May 1966		<i>Sargassum</i>	$0.24 \pm 0.08$
June 1966		<i>Sargassum</i>	$0.40 \pm 0.10$
March 1971		<i>Enteromorpha</i> spp	$4.36 \pm 0.20$
March 1971		<i>Gracilaria</i> spp	$3.03 \pm 0.10$
March 1971		<i>Sargassum</i>	$0.36 \pm 0.04$
January 1973		<i>Ulva lactuca</i>	$1.16 \pm 0.07$
January 1973		<i>Sargassum</i>	$0.54 \pm 0.04$
November 1973	Bangalore $12^{\circ} 4' \text{N}$ $74^{\circ} 30' \text{E}$ <sup>b</sup>	<i>Ulva lactuca</i>	$0.41 \pm 0.07$
November 1973		<i>Enteromorpha</i> spp	$1.47 \pm 0.22$

<sup>a</sup> Samples made available by Dr. S. Shastri, Tarapur Atomic Power Station, Tarapur.

<sup>b</sup> Samples made available by Dr. V. V. Naik, Dept. of Post Graduate Studies and Research in Biosciences, University of Mysore, Bangalore.

Soil samples from areas within a 25 km radius of the Research Centre were collected to obtain estimates of cumulative fall-out levels. Samples collected included those from the downwind direction of the Research Centre in order to assess the possible effect of the Fuel Reprocessing Plant at Trombay. The soil samples were collected from undisturbed areas. Soil from a 30 cm  $\times$  30 cm area was collected up to a depth of 5 cm. The samples were crushed, mixed and aliquots were treated with an HCl-HNO<sub>3</sub> mixture and the leachates were processed for plutonium. The  $^{137}\text{Cs}$  concentrations in the soils were also obtained by gamma-spectrometry. Only  $^{137}\text{Cs}$  was measured along with plutonium since it is known to have a similar distribution to that of plutonium in soils [14]. The deposited activities have been calculated and are given in Table III. The  $^{137}\text{Cs}$  deposition values ranged from 78 to 122 mCi/km<sup>2</sup> and  $^{239}\text{Pu}$  cumulative deposit ranged between 0.44 to 1.37 mCi/km<sup>2</sup>, except for one sample. The slightly higher values in one location could not be explained. The values of  $^{238}\text{Pu}$  to  $^{239}\text{Pu}$  ratios are also given in some cases. There was no pronounced variation in values among the samples from the downwind direction of the plant and those from other areas. The fall-out levels of  $^{137}\text{Cs}$  and the ratio of  $^{239}\text{Pu}$  to  $^{137}\text{Cs}$  in these samples indicate that plant operation has no effect on the deposited activity on soils in the surrounding areas.

Surface sediments, especially from shallow waters, are known to accumulate fall-out plutonium to a large extent since Pu gets quickly depleted from the water column overlying it. The bay sediments (surface grab samples) collected before the commissioning of the fuel-reprocessing facility were assayed for plutonium levels. A few sediment samples obtained from different geographic locations are also assayed for plutonium levels.

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The levels given in Table IV indicate the fall-out concentration of Pu in aquatic sediments in these areas. Since sediments accumulate most of the activity on their top layer, minor variations in the concentration levels are possible if the sediments get disturbed by physical or biological action. The lower Pu levels in Powai Lake surfaces in 1969 may be attributed to this possibility since the samples taken were gross grab samples.

Plutonium distribution in Bombay Harbour Bay

The Bombay Harbour Bay has been receiving low-level liquid effluents from the Irradiated Fuel Reprocessing Facility of the Bhabha Atomic Research Centre Trombay, for a decade. The major radionuclides in the low-level liquid effluents released are <sup>147</sup>Ce, <sup>137</sup>Cs, <sup>90</sup>Sr, <sup>106</sup>Ru and <sup>95</sup>Zr. Investigations carried out to study the behaviour of these nuclides in the bay environment and to assess the impact of such releases have been reported [15]. The effluents also contain traces of alpha activity of the order of 0.1% of the total activity, the major component of which is identified as plutonium.

Seawater and silt

Earlier studies have indicated that of all nuclides released into the Bay <sup>90</sup>Sr and <sup>137</sup>Cs are the predominant radionuclides found in the Bay waters. Ru and Ce nuclides were present only at very low concentrations even near the discharge location. Since Pu concentrations in water were also expected to be low, only a few samples from the discharge area were analysed for their Pu content. The surface samples collected were allowed to settle, the supernatant was filtered through Whatman No 42 filter paper and the Pu in the filtrate was estimated. Table V gives the concentrations of plutonium in seawater and silt and the ratios of <sup>137</sup>Cs and <sup>90</sup>Sr to that of <sup>239</sup>Pu in seawater and suspended silt. The average K<sub>d</sub> values (distribution coefficient) for Pu in suspended silt from seawater are also given.

The concentration in seawater is 10-100 times the fall-out concentration levels. However, it is observed that the ratios of other nuclides to that of plutonium are very much higher than the ratios reported for fall-out levels in ocean waters. Of all the nuclides released the maximum K<sub>d</sub> factor obtained was for Pu.

The silt load in the waters varies between 10 and 2800 mg/l, depending season and tidal conditions. On the basis of the K<sub>d</sub> value obtained for Pu (9 x 10<sup>6</sup>) and assuming a silt load of 1000 mg/l in Bay waters a decontamination factor of 90 is obtained for plutonium [15]. Thus nearly 99% of the released Pu is likely to be accumulated in suspended silt, shore or bottom sediments.

Sediments

The shore sediments of the Bay were also examined for the accumulation of Pu [16]. The accumulation is influenced by the discharge rates and by seasonal variations. The plutonium accumulation is about 10 to 100 times higher than the fall-out levels observed in surface sediments from other areas near Bombay. The accumulation of Pu along the shore sediments had indicated earlier [16] that Pu is localized near the discharge point.



TABLE II PLUTONIUM IN RAIN WATER SAMPLES COLLECTED AT BOMBAY

Period of collection	Rainfall (cm)	Total collection (l)	$^{239}\text{Pu}$ ( $\mu\text{Ci/l}$ )	$^{240}\text{Pu}$ ( $\mu\text{Ci/l}$ )	$^{239}\text{Pu}$ de position ( $\text{mCi}/\text{km}^2$ )	$^{239}\text{Pu}/^{240}\text{Pu}$
June to September 1969	218	10.43	0.01 $\pm$ 0.0008	0.0014 $\pm$ 0.0001	0.022 $\pm$ 0.0004 <sup>1</sup>	0.14
June to September 1971	101.6	19.16	0.062 $\pm$ 0.011	-	0.083 $\pm$ 0.011	-

TABLE III CUMULATIVE DEPOSITION OF PLUTONIUM AND  $^{137}\text{Cs}$  IN SOILS FROM AREAS AROUND THE RESEARCH CENTRE

Date of collection	Location	$^{239}\text{Pu}$ ( $\mu\text{Ci}/\text{kg dry}$ )	$^{240}\text{Pu}$ ( $\mu\text{Ci}/\text{kg dry}$ )	$^{239}\text{Pu}/^{240}\text{Pu}$	$^{239}\text{Pu}$ ( $\text{mCi}/\text{km}^2$ )	$^{137}\text{Cs}$ ( $\text{mCi}/\text{km}^2$ )
March 1974	Bcomr	6.0 $\pm$ 0.82	1.04 $\pm$ 0.1	-	0.11 $\pm$ 0.072	-
May 1974	Telecom factory	14.6 $\pm$ 1.7	12.7 $\pm$ 1.9	-	1.07 $\pm$ 0.12	-
July 1974	Mankhurd village	14.79 $\pm$ 1.75	2.21 $\pm$ 0.11	0.13	1.21 $\pm$ 0.16	1.7 $\pm$ 100
August 1974	Belapur village	11.11 $\pm$ 0.67	1.77 $\pm$ 0.17	0.156	1.01 $\pm$ 0.08	6.1 $\pm$ 6.6
August 1974	Belapur Hill top	7.51 $\pm$ 0.55	0.91 $\pm$ 0.14	0.12	0.19 $\pm$ 0.01	26.1 $\pm$ 6.0
October 1974	Bhandup	17.76 $\pm$ 2.23	4.92 $\pm$ 0.80	0.27	1.37 $\pm$ 0.2	109.1 $\pm$ 6.9

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TABLE V. ACCUMULATION OF  $^{137}\text{Cs}$  AND  $^{239}\text{Pu}$  IN BOTTOM SEDIMENTS 1970 COLLECTED PARALLEL TO THE SHORE ON EITHER SIDE OF THE DISCHARGE LOCATION

Station	$^{137}\text{Cs}$ (dpm/g)		$^{239}\text{Pu}$ (dpm/g)	
	Surface	Depth	Surface	Depth
1	1.2	0.8	0.1	0.1
2	0.8	0.5	0.05	0.05
3	0.5	0.3	0.03	0.03
4	0.3	0.2	0.02	0.02
5	0.2	0.1	0.01	0.01

The bottom sediments (surface grab samples collected from the Bay during the pre-monsoon months of 1968 and 1970) indicate that Pu along with other radionuclides, is mostly accumulated in the bottom sediments of the stream flowing near Trombay. The accumulation of radionuclides in bottom sediments taken from the coastal stream from stations parallel to the shore on either side of the discharge location is given in Table V. The concentration in these sediment samples indicates a reduction in the levels of activity with increasing distance from discharge location. The ratios of  $^{137}\text{Cs}/^{239}\text{Pu}$  at different locations indicated the preferential localization of Pu relative to  $^{137}\text{Cs}$ .

The distribution of  $^{137}\text{Cs}$  and  $^{239}\text{Pu}$  in a Bay core sample taken from a location at a distance from the discharge area is given in Fig 1. Even though there is a uniform decrease in  $^{137}\text{Cs}$  values with depth the Pu concentrations do not show a corresponding decrease at all depths, indicating possible downward migration of Pu in the sediment. Evidently more studies are required to confirm the behaviour and to understand the mechanisms of this downward movement.

#### Organisms

The accumulation of plutonium by different Bay organisms were studied by periodic collection of some species from the Bay. Most of the organisms were collected from areas close to the discharge location. The organisms were thoroughly cleaned, especially the benthic organisms like crab and arca, were carefully cleaned to free them from trapped sediment. The dried samples were gamma-counted using a NaI detector and a 512-channel analyser. The dried samples were analysed for  $^{239}\text{Pu}$  and in some cases for  $^{90}\text{Sr}$ .

Tables VII and VIII give the accumulation of Pu in various species. The ratios of  $^{90}\text{Sr}/^{239}\text{Pu}$  and  $^{137}\text{Cs}/^{239}\text{Pu}$  are also given. Plutonium concentrations in some species obtained from outside the Bay are also included.

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TABLE VII ACCUMULATION OF PLUTONIUM IN COASTAL ORGANISMS

Date of collection	Location	Species	Part analysed	$^{239}\text{Pu}$ (ppm (dry wt))	$\frac{^{239}\text{Pu}}{^{240}\text{Pu}}$	$\frac{^{240}\text{Pu}}{^{239}\text{Pu}}$
1 November 1970	Offshore	Mackerel	Flesh	0.5	108	11
			Bone	2.8		5
2 December 1974	Outside bay	Catfish ( <i>Arius</i> sp.)	Flesh	0.7	21.1	97
			Bone	1.8	5.1	16
3 September 1970	Trombay Naval Jetty	Crab ( <i>Scylla serrata</i> )	Flesh	1.6	1150	2119
			Bone	2.5	16.2	1208
4 June 1971		Crab ( <i>Scylla serrata</i> )	Flesh	1.1		16.76
			Bone			
5 June 1971		Catfish ( <i>Arius</i> sp.)	Flesh	0.1	-	71000
			Bone	1.0	-	10111
			Gut	2.1	-	11110
6 November 1971	CRUIS	Catfish ( <i>Arius</i> sp.)	Flesh	5.5	31	6211
			Bone	21.0	187	2536
7 December 1974	Mahul	<i>Tilapia mosambica</i>	Whole	1.5	2.7	70

TABLE VIII ACCUMULATION OF PLUTONIUM IN ARC A (*Andru ligmosa*) FROM AIR AS CLOSE TO THE DISCHARGE LOCATION IN THE BAY

Date of collection

Time

Day

Year

TABLE VIII ACCUMULATION OF PLUTONIUM IN ARCA (And in a few mos.) FROM AIR AS CLOSI TO THE DISCHARGE LOCATION IN THE BAY

Date of collection	Location	Part analysed	$^{239}\text{Pu}$ ( $\mu\text{g}/\text{kg wet}$ )	$^{240}\text{Pu}$ ( $\mu\text{g}/\text{kg wet}$ )	$^{241}\text{Pu}$ ( $\mu\text{g}/\text{kg wet}$ )	$\frac{^{240}\text{Pu}}{^{239}\text{Pu}}$	$\frac{^{241}\text{Pu}}{^{239}\text{Pu}}$
November 1971	Discharge area	Flesh	67.2	-	11.0	-	191
		Shell	7.9	-	ND	-	-
June 1972	Trombay Naval Jetty	Flesh	11.9	0.41	6.91	1.1	111
		Shell	11.1	102.9	ND	7717	-
December 1972	1 km north of discharge point	Flesh	11.9	-	2.26	-	111
		Shell	21.2	-	ND	-	-
December 1972	Discharge area	Flesh	40.5	-	1.17	-	111
		Shell	115.7	117.6	ND	2.116	-
December 1972	1 km south of discharge point	Flesh	-	-	1.77	-	-
		Shell	14.81	-	ND	-	-
January 1974	Trombay Naval Jetty	Flesh	1.1	0.19	0.71	110	9
		Shell	2.5	0.25	1.9	7	71
June 1975	Trombay	Flesh	15.0	0.01	0.46	1	1
		Shell	18.1	76.1	2.10	126	112

(Arctus sp.)  
 Whole  
 7 December 1971  
 Mumbai  
 6871  
 2.7  
 68  
 70

TABLE IX CONCENTRATION OF PLUTONIUM IN SOLAR SALT OBTAINED FROM THE BAY WATERS

Location	Date of sample	Fraction analysed	<sup>239</sup> Pu concentration (μg of salt)
Beira	1972-1-17	soluble portion	< 0.01
		silt	0.04 ± 0.01 (0.1 μC of silt)
Murtola	1972-1-17	soluble portion	0.15 ± 0.05
		silt	0.35 ± 0.10 (0.20 μC of silt)

The <sup>137</sup>Cs / <sup>239</sup>Pu ratios in arca flesh were lower than in seawater, again indicating a possible pathway of these radionuclides through sediments. However, for other species the ratios were higher by 1 to 2 orders of magnitude, showing the preferential uptake of <sup>137</sup>Cs in flesh over <sup>239</sup>Pu.

Salt

Salt samples obtained from salt pans located on the coastline of the Bay, one each on either side of the Bay were examined for possible accumulation of plutonium. Table IX gives the concentration of Pu in the soluble fraction of crude salt and the insoluble silt. Only the salt from the pan nearer to the discharge location showed a detectable concentration of Pu. However, silt from the salt in both cases showed a higher concentration of Pu. Earlier studies have shown that salt from different salt pans reflected the radionuclide and trace element concentrations at different locations in the Bay [17].

INTERACTION OF PLUTONIUM IN SEAWATER

Behaviour of discharged plutonium in the aquatic environment is likely to vary depending upon the environmental conditions and the source of plutonium introduced. It is known that, depending upon its state, the toxicity of plutonium also varies. This assumes significance in the context of biological uptake of the element.

Andelman and Rozzell [18] and Polzer [19] have discussed the nature of plutonium in water environments. Our earlier studies have shown that solubilisation of plutonium in aquatic media depends upon the nature of the plutonium-containing solution introduced. The predominant dissolved plutonium species is dependent on the specific environmental conditions. Carbonates in water can complex plutonium and keep them in solution. However, the effects of naturally occurring organic matter present in seawater have not been studied. The aging effect of Pu in solutions was

studied and... However... countered... After... seawater... in Bay waters... studied as... taking place... studies... me as (20... sediments... from sediments... Seawater... substances... purified organic...

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Table XI give... solubilization of P... nearly two orders... interacted with se...



TABLE X SOLUBILITY AND IONIC STATES OF PLUTONIUM IN SEAWATER AT DIFFERENT INTERVALS OF TIME

No	Experiment	Time after mixing (d)	Insoluble Pu (dpm/100 ml)	Insoluble (%)	Soluble plutonium				
					Pu content (dpm/100 ml) (Molar conc.)	Non-ionic (%)	Non-ionic (%)	Non-ionic (%)	
1	Pure plutonium solution + Millipore filtered seawater mixed pH 7.4-7.8 throughout the experiment	0	186.1	55.88	149.16	$1.61 \times 10^{-11}$	-	16.2	8.1
		1	215.6	63.19	129.42	$4.02 \times 10^{-11}$	12.1	25.9	11.8
		10	261.0	81.10	10.36	$1.88 \times 10^{-11}$	61.6	19.1	11.1
		30	261.4	81.10	12.73	$1.12 \times 10^{-11}$	60.6	11.2	12.1
2	Pure plutonium solution + Millipore filtered seawater + 20 mg of organic matter extracted from sediments mixed pH 7.4-7.8 throughout the experiment	0	86.2	27.85	2.61	$7.1 \times 10^{-11}$	17.6	21.7	13.0
		1	81.0	20.61	111.2	$9.68 \times 10^{-11}$	15.0	12.1	23.1
		10	87.0	17.56	389.5	$1.1 \times 10^{-11}$	71.3	18.0	6.1
		30	108.6	30.15	248.1	$7.7 \times 10^{-11}$	8.9	19.0	11.1

TABLE XI SOLUBILITY AND IONIC STATES OF PLUTONIUM (CONTAINED IN FILTERED SEAWATER) AT DIFFERENT INTERVALS OF TIME

TABLE XI SOLUBILITY AND IONIC STATES OF PLUTONIUM (CONTAINED IN EFFLUENTS) IN SEAWATER AT DIFFERENT INTERVALS OF TIME

No	Experiment	Time after mixing	Soluble plutonium				
			Pu concentration (dpm/100 ml)	Pu concentration (Molar conc.)	Non-cationic (%)	Non-anionic (%)	Non-ionic (%)
1	1 ml of effluent + 200 ml of filtered seawater	15 min	1.4	$1.17 \times 10^{-12}$	51.5	51.1	11.6
	1 ml of effluent + 200 ml of filtered seawater	15 d	1.5	$1.09 \times 10^{-12}$			
	1 ml of effluent + 200 ml of filtered seawater	15 d	4.1	$1.33 \times 10^{-12}$			
	1 ml of effluent + 200 ml of filtered seawater	12 months	1.1	$1.17 \times 10^{-12}$	87.50	12.50	0.0
	1 ml of effluent + 200 ml of filtered seawater + 3.5 mg of organic matter	15 months	1.8	$1.19 \times 10^{-12}$	100.0	10.67	16.67
2	5 ml of effluent mixed with 100 ml of filtered seawater	1 d	1.8	$5.1 \times 10^{-11}$			
	10 ml of effluent + 200 ml of filtered seawater	1 d		$2 \times 10^{-11}$	11.2	11.1	1.1
	1 ml of effluent + 1000 ml of filtered seawater	7 d			83.33	11.11	10.56

15

TABLE XII. INTERACTION OF PLUTONIUM WITH ORGANIC MATTER

Experiment	Time after mixing (d)	Insoluble Pu (dpm/5 ml)	Soluble plutonium			
			Soluble Pu conc. (dpm/5 ml)	Non-cytotoxic (%)	Non-mitogenic (%)	Pu solubilized (µg/mg of OM)
Pure Pu solution + 25 ml of organic matter extract (1 ml = 0.77 mg OM) pH 7.0	7	20	66.6	100	0	$2.7 \times 10^{-4}$
	46	10.6	60.1	100	0	$2.1 \times 10^{-4}$

TABLE XIII. PLUTONIUM IN THE ORGANIC FRACTION OF COASTAL SEDIMENTS

Date of sampling	Location	Amount of sediment used for extraction of organic matter (g)	Total Pu content (dpm)	Pu in organic fraction of sediment (dpm)	U to Pu ratio of sediment (µg)	% Pu in organic matter	
						org. in. matter	% U to Pu
November 1970	Near CRIS	33.2	4.15	0.16	1.61	0.4	1.11
November 1971	Near discharge location	10.0	16.0	1.21 <sup>a</sup>	-	7.5	-

<sup>a</sup> Total organic matter extracted 65.7 mg.

the removal. Therefore, it is likely that seawater suspended solids less soluble and less complexed effect was added to seawater after a period.

In the case of (Table XI)  $2.7 \times 10^{-4}$  µg

In all the observed. The organic Pu. The relative biological Pu exists with respect

#### Plutonium

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The removal of Pu along with other fission products present in the effluent. There are the introduction of such effluents into the aquatic environment is likely to result in lower concentrations of plutonium in soluble form in seawater. This in turn will be further reduced as a result of sorption by suspended solids in coastal regions. The species obtained were more or less same as in the case of pure Pu solutions. The non-ionic species were less compared with those obtained at higher Pu concentrations. The aging effect was also less pronounced in this case. When organic matter was added to seawater it was observed that cationic species were not detectable after a period of 15 months and about 90% were in the anionic form.

In the case of direct interaction of Pu with organic matter extract (Table XII) it was found that 1 mg of organic matter solubilizes about  $2.7 \times 10^{-4}$   $\mu$ g of Pu. All the Pu had been converted to anionic form.

In all these experiments Pu sorption on to glass surfaces has been observed. The calculations were made on the basis of Pu in solution. The organic matter added to seawater changed the ionic species of added Pu. The tendency for hydrolysis and subsequent removal was reduced. The relative influence of carbonates and organic matter in coastal water has to be studied. Further information is needed on the chemical and biological behaviour of these species in the aquatic environment. Since Pu exists in multivalent states, it is also necessary to know the interaction with respect to the different valency states.

Plutonium in coastal sediments

Studies reported earlier showed that sediments have a very high accumulation capacity for plutonium and more than 99% of the released plutonium gets locked up in coastal sediments. It is necessary to know the possible ways by which these accumulated nuclides can be released into the aqueous phase.

After treating with uncontaminated filtered seawater and stirring mechanically for periods up to 8 hours and examining the filtrate for plutonium content, sediments did not release any plutonium into seawater. Therefore it is unlikely that when sediments are transported to other areas plutonium will be released into the water.

Leaching the coastal sediments with 8M HNO<sub>3</sub> has been found to remove Pu quantitatively from sediments. This was confirmed by decomposing the residue and estimating the Pu [16]. It is to be expected that since most of the Pu deposited on sediments is the result of scavenging of the hydrolysed products of Pu in seawater, acid leaching should be able to remove all Pu.

A sediment sample was examined for the possible presence of Pu in the easily oxidizable organic fraction of the sediment. This was investigated by treating the sediment slurry with H<sub>2</sub>O<sub>2</sub> at 80°C in the presence of N/20 HCl so as to adjust the pH to 5.8. The solution was allowed to settle and the filtrate (0.22  $\mu$ m) was analysed for its <sup>239</sup>Pu content after addition of internal tracer <sup>236</sup>Pu. The alpha spectrum of the separated Pu showed no trace of <sup>239</sup>Pu, indicating that Pu has not been released from the sediment as a result of H<sub>2</sub>O<sub>2</sub> oxidation. It is, however, known that H<sub>2</sub>O<sub>2</sub> does not oxidize all the organic matter in the sediment. There is also a likelihood of the released Pu becoming resorbed on the sediment particles.

To ascertain the possible presence of plutonium in the organic fraction of the sediment, contaminated sediments were treated with alkali to extract

Total organic matter extracted 85.7 mg



and the residue counted for d in the purified th organic d from sediments compared to

cted after a ring the purified num was ch higher than the possibility nd its possible ued to confirm

There are uncertainties regarding the absorption of Pu from the GI tract. For soluble compounds this factor is estimated to be  $3 \times 10^{-3}$ . However, Pu complexes can be absorbed to the extent of 2% [25]. Most of these data have been obtained in laboratory experiments with animals. Pu is likely to be protein bound in organisms. It is necessary to obtain data on absorption factors for the GI tract when Pu is ingested through contaminated food. Since age may also influence absorption [25] this aspect also needs further investigation.

In silt-laden coastal waters biological uptake and transport might be insignificant. Silt movement will be the major transport mechanism by which Pu will be translocated from the discharge area. Owing to the high  $K_d$  factors in sediment and non-leachability with seawater Pu would be a good tracer for studying silt transport. As the major depository of all released Pu in aquatic environments, sediments need further study to understand their biological and geochemical significance.

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#### REFERENCES

- [1] DIAMOND H. et al. Heavy isotope abundances in Nike Thermonuclear Device. *Phys. Rev.* **119** (1960) 2000.
- [2] HARDY E. P., KREY W. P., VOLCHOK, H. L. Global inventory and distribution of fallout plutonium. *Nature (London)* **24** (1973) 44.
- [3] NOSHKIN V. E. Ecological aspects of plutonium dissemination in aquatic environments. *Health Phys.* **22** (1972) 537.
- [4] HETHERINGTON J. A., JEFFERIES D. F., LOVETT M. B. Some investigations into the behaviour of plutonium in the marine environment. *Radiological Impacts of Releases from Nuclear Facilities into Aquatic Environments (Proc. Symp. Helsinki 1975)*. IAEA, Vienna (in press).
- [5] *Radioactive Wastemanagement Practices in Western Europe*. ENEA Rep (1971).
- [6] PRESTON A. The radiological consequences of releases from nuclear facilities to the aquatic environment. *Radiological Impacts of Releases from Nuclear Facilities into the Aquatic Environments (Proc. Symp. Helsinki 1975)*. IAEA, Vienna (in press).
- [7] KREY W. P., BOGEN D., FRENCH E. Plutonium in man and his environment. *Nature (London)* **201** (1962) 263.
- [8] THOMAS C. W., REID D. L., LUST L. F. Radiochemical Analysis of Marine Biological Samples Following the Redwing Shot Series. Rep. HW-5674 (1956).
- [9] TEMPLETON W. L., PRESON A. "Transport and distribution of radioactive effluents in coastal and estuarine waters of the United Kingdom". *Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters (Proc. Symp. Vienna 1966)*. IAEA, Vienna (1966) 267.
- [10] PILLAI K. C., SMITH R. C., FOLSOM T. R. Plutonium in the marine environment. *Nature (London)* **203** (1964) 568.
- [11] INTERNATIONAL ATOMIC ENERGY AGENCY. Reference Methods for Marine Radioactivity Studies II. Technical Reports Series No. 169, IAEA, Vienna (1975).

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- [12] WONG K V, HODGE F, FOLSOM T R. Concentrations of plutonium, cobalt and silver actinonulides in selected pacific sea weeds. Proc Environmental Plutonium Symp, CROWLER B E, HENDERSON R W, VILLIGAN F M, Eds, LASL 1971
- [13] LALIT B V, CHANDRA-EKHARAN V P. Radioactive Contamination of Bombay Tap Water. Rep HASL-264 (1971)
- [14] HAFDY E. Depth distribution of global fallout  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$  and  $^{239, 240}\text{Pu}$  in sandy loam soil. HASL-268 (1974)
- [15] PILLAI K C, DEVEN N, MATHEW E, KOTHARI B C. Behaviour of dissolved actinonulides from fuel reprocessing operations in the aquatic environment of the Bombay harbour bay. Radiological Impacts of Releases from Nuclear Facilities into Aquatic Environments. Proc Symp Helsinki 1970, IAEA Vienna (in press)
- [16] PILLAI K C. Determination of plutonium in the marine environment. Reference Methods for Marine Radioactivity Studies II. Technical Reports Series No 169, IAEA Vienna (1970) 97
- [17] GANAPATHY S, KOTHARI B C, PILLAI K C. Solar salt as a medium for transfer of radio-nulides and trace elements to man. presented First Asian Regional Congress on Radiation Protection Bombay 1974
- [18] ANDELMAN J B, ROZZELL T C. Plutonium in the water environment. Ch 8. Radionulides in the Environment. Advances in Chemistry Series 93, ROBERT F G, Ed (1970) 13
- [19] POLZER W L. Solubility of Plutonium in soil/Water Environment. Rep HASL-e340 (1971)
- [20] KOSHY E, DESAI, M M, GANGULY A K. Studies on organo-metallic interactions in the marine environment. Part I - Interactions of some metallic ions with dissolved organic substances in sea water. Curr Sci (1969) 555
- [21] GANAPATHY S, PILLAI K C, GANGULY A K. Adsorption of Trace Elements by Near shore Sea Bed Sediments. Rep BARC-376 (1968)
- [22] DESAI M M, GANGULY A K. Organic and organo-metallic substances in the marine environment. presented Symp Interaction Between Water and Living Matter. Odessa 1975
- [23] KOSHY E, GANGULY A K. Organic Materials in the Marine Environment and Their Interactions with Some Metal Ions. Rep BARC-402 (1969)
- [24] PILLAI K C. Aquatic pollution control systematics for discharge of radioactive effluents. Proc COST Seminar on Pollution and Human environment. BARC Bombay (1970)
- [25] ICRP. The Metabolism of Compounds of Plutonium and Other Actinides. Publication 19 Pergamon Press New York (1972) 13

#### DISCUSSION

A A MOGHISSI. You say that plutonium constituted only a minor fraction of the total releases. Could you express your release values in terms of their environmental significance, however, allowing for the fact that plutonium represents a greater environmental hazard than other radionulides?

K C PILLAI. I feel one should look at the final values of plutonium in the organism to understand its environmental significance. The average concentrations of  $^{90}\text{Sr}$  and  $^{239}\text{Pu}$  in the flesh of clams collected from areas close to the discharge location is only 1.24 and 0.01%, respectively, of the limiting values of these nuclides, and this is indeed low. Even here, the plutonium contribution to radiation exposure (for a person consuming these organisms) is 125 times less than that of  $^{90}\text{Sr}$ .

Y NISHIWAKI. In Table II you give the results of measurements of plutonium in rainwater collected at Trombay. I should like to ask you whether these values represent only the fraction of plutonium deposited with rain all or whether they also include dry deposition. I should also like to know about the possibility of plutonium resuspended in the atmosphere by wind being counted again, given the method of sample collection used in your experiment. What would be the soluble and insoluble fractions of plutonium included in the Trombay rainwater samples?

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VIENNA, 1976

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