PANEL ON RADIATION EFFECTS ON
POPULATIONS DYNAMICS IN ECOSYSTEMS

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ABSTRACT

EFFECTS ON AQUATIC BIOTA OF RADIOACTIVE EFFLUENTS
FROM NUCLEAR POWER STATIONS*

B. G. Blaylock
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Radioactive effluents released from nuclear power stations are one of the most rapidly increasing potential sources of radiation exposure to aquatic organisms. This paper considers the radiation dose to aquatic organisms living in an area receiving radioactive wastes from a representative nuclear power station, the effects of this dose, and the possible synergistic effects of radiation and temperature. Data used are from selected publications covering the effects of chronic low-level radiation and other environmental pollutants.

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INTRODUCTION

The effect of radioactive effluents on aquatic ecosystems is one of the primary considerations when evaluating the impact of nuclear generating stations. Although the effect of radiation may be the most publicized and the most intensely studied, other effluents from nuclear power stations may produce a more deleterious impact on the aquatic ecosystem. Under normal operating conditions nuclear power stations release large volumes of heated water used for cooling condensers and chemicals used as biocides and for other plant operations.

Biological damage to aquatic ecosystems can result from radioactive effluents, heated water, and chemical releases; there is also the possible synergistic effect, that is, the combination of the above stresses which may cause effects greater than the sum of the individual effects.

The objectives of this paper are: (1) To discuss the level of radiation received by aquatic biota in the vicinity of nuclear power plants. (2) To evaluate the possible effects of this dose from radioactive effluents. (3) To consider the synergistic effects of radiation and temperature.

Radiation Dose

Aquatic biota living in the vicinity of nuclear power stations will be exposed to low levels of radioactivity released in the liquid effluents. The organisms will receive a radiation dose from internal emitters as a result of radionuclides assimilated from food and absorbed from water. External exposure will result from immersion in water that contains the radioactivity; in addition some types of biota will receive an external exposure from radionuclides accumulated in sediments.

The concentrations of radionuclides used in calculating doses to the aquatic biota are given in Table 1. These data are from Booth et al. 1972 [1] who used information from 15 operating power stations (both pressurized water reactors and boiling water reactors) to identify 62 radionuclides and determine their respective annual release rates in discharge canals. Only the 11 radionuclides (listed in Table 1) which were shown to contribute the major part of the radiation dose were used in determining the level of radiation received by aquatic biota. Since the concentrations of radionuclides will decrease as the discharged effluents mix with the receiving body of water thereby reducing the radiation dose to the biota, the maximum concentrations to which the aquatic biota might be exposed were used in the dose calculations.

All dose calculations assume steady state conditions (i.e., radionuclide concentrations in water remain constant). Most radionuclides in the biota reach equilibrium; therefore, radionuclide concentrations should not increase indefinitely in an environment where the input of radioactive material is constant.

Since aquatic organisms may concentrate radionuclides in their tissues to higher levels than the concentration of radionuclides in the ambient water, the dose from internal emitters will contribute the

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Table 1. Internal Radiation Dose to Aquatic Biota Based on Representative Radioactivity Released into Discharge Canals of Nuclear Power Stations

Radionuclide	Concentration ($\mu\text{Ci/ml}$)	Internal Dose (millirads/year)		
		Aquatic Plants	Invertebrates	Fish
^{46}Sc	1.0×10^{-11}	2.4	2.4×10^{-1}	2.4×10^{-2}
^{54}Mn	9.5×10^{-12}	3.2	1.3×10^1	2.3×10^{-3}
^{58}Co	1.7×10^{-10}	4.8	2.9	9.7×10^{-1}
^{60}Co	4.8×10^{-11}	3.4	2.0	6.7×10^{-1}
^{91}Sr	2.4×10^{-11}	2.8	3.8	1.4×10^{-1}
^{91}Y	2.0×10^{-11}	2.2	2.2×10^{-1}	2.2×10^{-2}
^{131}I	4.2×10^{-11}	6.9×10^{-2}	3.5×10^{-1}	1.7×10^{-2}
^{133}I	8.4×10^{-11}	2.6×10^{-1}	1.3	6.6×10^{-2}
^{134}Cs	1.3×10^{-11}	6.7	2.9	2.7×10^{-1}
^{135}I	9.0×10^{-11}	4.4×10^{-1}	2.2	1.1×10^{-1}
^{137}Cs	2.0×10^{-11}	5.5	2.4	2.2×10^{-1}
Total Dose		3.177×10^1	3.13×10^1	2.5

major part of the dose to the organisms. The bioaccumulation factors [2-4] used in the dose calculations for aquatic plants, invertebrates and fish are shown in Table 2. These factors represent the upper limits found in the literature except for a few radionuclides which have a body of data which supports less than the highest found. In actual exposure situations, the bioaccumulation factors are expected to be smaller because of dietary dilutions by noncontaminated foods or because of consumption of aquatic plants with bioaccumulation factors lower than those assumed.

The annual internal dose (millirads/year), D_i , from the i^{th} radionuclide to biota that derives all its food from water at W_i $\mu\text{Ci/ml}$ with which it is in equilibrium is written

$$D_i = (1.87 \times 10^7) W_i C_i^b E_i \text{ (millirads/year)}$$

where

1.87×10^7 = constant to convert microcuries per gram of biota to dose,

C_i^b = bioaccumulation factor $[(\text{g of H}_2\text{O})/(\text{g of biota})]$ for the biota (the index $b = f$ for fish, $= i$ for invertebrates, and a for aquatic plants),

E_i = the effective absorbed energy of the i^{th} radionuclide in the biota, MeV.

The maximum effective absorbed energies (30-cm-diam organism) in man were used to calculate doses to organisms in the general categories of aquatic plants, invertebrates, and fish. Therefore, for most organisms, the internal dose will be considerably overestimated because the effective absorbed energy will be less than that for a 30-cm-diam organism.

The total calculated internal doses to aquatic plants, invertebrates, and fish are 32.0, 31.0 and 2.5 millirads/year respectively, (Table 1). The total dose from all 62 radionuclides measured in the discharge canals was only slightly greater (37.0 for aquatic plants, 35.0 for invertebrates and 4.3 for fish).

The external dose from beta and gamma radiation for continuous immersion of any organism in water was estimated with the EXREM Computer Code [5] to be 0.015 millirad/yr (Table 3). The total dose accumulated by the aquatic biota would be less than the dose received from background radiation. All these calculated doses are believed to represent upper-limit estimates because equilibrium was assumed to exist between all organisms and all radionuclides in the water in the vicinity of a nuclear power station. (A nonequilibrium situation would result in a lower concentration of radioactivity in tissue and thus a lower dose.)

Effects of Chronic Radiation on Natural Populations

Most of the studies which have been made on natural populations exposed to chronic radiation higher than background have been conducted at the Oak Ridge National Laboratory (ORNL). Studies have been conducted

Table 2. Bioaccumulation Factors for Biota
in an Aquatic Environment *

Radionuclide	Aquatic Plants	Invertebrates	Fish
^{46}Sc	1.0×10^4	1.0×10^3	1.0×10^2
^{54}Mn	3.5×10^4	1.4×10^5	2.5×10^1
^{58}Co	2.5×10^3	1.5×10^3	5.0×10^1
^{60}Co	2.5×10^3	1.5×10^3	5.0×10^1
^{91}Sr	3.0×10^3	4.0×10^3	1.5×10^2
^{91}Y	1.0×10^4	1.0×10^3	1.0×10^2
^{131}I	2.0×10^2	1.0×10^3	5.0×10^1
^{133}I	2.0×10^2	1.0×10^3	5.0×10^1
^{134}Cs	2.5×10^4	1.1×10^3	1.0×10^3
^{135}I	2.0×10^2	1.0×10^3	5.0×10^1
^{137}Cs	2.5×10^4	1.1×10^3	1.0×10^3

Table 3. Water Immersion Dose to All Biota Based on Representative Radioactivity Releases into Discharge Canals of Nuclear Power Stations

Radionuclide	Concentration ($\mu\text{Ci/ml}$)	Dose (millirads/year)	
		Beta and Gamma	Gamma
^{46}Sc	1.0×10^{-11}	3.8×10^{-4}	3.8×10^{-4}
^{54}Mn	9.5×10^{-12}	1.5×10^{-4}	1.5×10^{-4}
^{58}Co	1.7×10^{-10}	3.1×10^{-3}	3.1×10^{-3}
^{60}Co	4.8×10^{-11}	2.3×10^{-3}	2.2×10^{-3}
^{91}Sr	2.4×10^{-11}	8.0×10^{-4}	5.2×10^{-4}
^{91}Y	2.0×10^{-11}	1.1×10^{-4}	1.4×10^{-4}
^{131}I	4.2×10^{-11}	3.9×10^{-4}	3.1×10^{-4}
^{133}I	8.4×10^{-11}	1.3×10^{-3}	9.3×10^{-4}
^{134}Cs	1.3×10^{-11}	4.1×10^{-4}	3.8×10^{-4}
^{135}I	9.0×10^{-11}	5.6×10^{-3}	5.5×10^{-3}
^{137}Cs	2.0×10^{-11}	2.6×10^{-4}	2.3×10^{-4}
Total Dose		1.477×10^{-2}	1.384×10^{-2}

on populations of fish, snails and insects that inhabit White Oak Lake. This lake located on the Oak Ridge Reservation has served as a final settling basin for low-level radioactive waste effluents from ORNL since 1943 [6]. The natural populations of organisms which live in this environment have been exposed to chronic radiation for many generations, and the levels of radioactivity in White Oak Lake is much greater than is expected in the vicinity of nuclear power stations [7].

Fecundity, one of the parameters of fitness, was measured in mosquito fish, Gambusia affinis affinis, from White Oak Lake and compared with a control population [8]. Approximately one hundred generations of Gambusia have lived in this area since the first release of radioactive waste effluents. Gambusia living in the upper shallow portion of White Oak Lake where the sediments contained appreciable quantities of ^{137}Cs , ^{106}Ru , ^{60}Co , ^{90}Sr , ^{65}Zn were estimated to receive approximately 11 rads per day.

Females of Gambusia, which is an ovoviviporous species, were dissected shortly before they were to give birth to their young and the numbers of viable embryos, dead embryos, and abnormal embryos were scored. Although there was a significantly greater number of dead and abnormal embryos in the irradiated population, there was also a significantly greater number of viable embryos relative to the control group. It was suggested that the increased fecundity of the female in the Gambusia population in White Oak Lake may be an adjustment to the increased mortality of embryos and could be attributed to radiation. In this respect radiation would be analogous to an environmental factor that increased mortality rates.

Similar results have been found by Donaldson at the University of Washington [9] in long-term studies on the effect of chronic low-level gamma radiation on the chinook salmon (Oncorhynchus tshawytscha). More of the salmon that were irradiated in the embryonic stage with 0.5 rad/day returned to spawn and produce a greater number of eggs than control fish produced.

In another study conducted on the snail, Physa heterostropha, in White Oak Lake, Cooley [10] found an increased number of eggs per capsule but a decrease in the number of egg capsules per snail. The radiation dose received by these snails at the time of the study was calculated as 0.65 rad/day; however, the population had been exposed to higher doses in the past. Data from the field study supported by laboratory experiments led Cooley to hypothesize that the reduced frequency of capsule production is compensated for by the increased number of eggs per capsule.

Three examples have been given which demonstrate an increase in some parameter of fitness of an organism which is attributed to the effects of chronic low-level radiation. Other evidence has accumulated to show that under certain conditions radiation exposure can increase the fitness of organisms [11-15]. This evidence cannot be completely ignored when assessing the effects of radioactive effluents of a nuclear power station on the aquatic biota but must be considered as it relates to the aquatic ecosystem.

Effects of Chronic Radiation on Organisms in Laboratory Experiments

The effects of chronic radiation at low dose rates are difficult to detect. A series of experiments were conducted to determine the effects of 1, 10 and 25 rads/hour on the survival, size, and reproduction of the snail Physa heterostropha [10]. A dose rate of 1 rad/hour produced no significant effect on reproduction (egg capsule/snail, eggs/capsule, eggs/snail, and percentage of eggs hatched), mortality, or size of the snail. Although the lowest dose rate did, however, give indications of causing a reduced fecundity, a dose rate of 10 rads/hour significantly decreased all of these factors.

The effects of chronic irradiation on the mosquito fish were investigated [16]. The fish received a dose of 1.3, 2.5 or 5.4 rads/hour for a period of 47 days. No excessive mortality occurred at any of the doses when compared with the controls although some fish received over 500 rads. After 47 days the surviving fish were sacrificed for pathological studies of hemopoietic and reproductive organs. No histological effects were detected in the hemopoietic organs (kidney or spleen) or ovaries. Atrophy of the testes was detected after 18 days at all dose rates including the lowest dose rate of 1.3 rads/hour. No other histological effects of chronic radiation were seen. Based on the results of this experiment and the preceding experiments, it would be exceedingly difficult to detect these types of effects at the dose rate calculated for aquatic biota in the vicinity of a nuclear power station.

Genetic Effects

If it is accepted that the mutation rate in organisms is linear in relation to radiation dose and that there is no threshold value for the production of mutations, an increase over the background levels of radiation would increase the mutation rate. However, little information is available on the mutation rates of chronic radiation. At 0.009 rad/min (12.9 rads/day), Russell [17] found a mutation rate in mice of 5.6×10^{-8} mutation/locus/rad. Purdom [18] concluded that the spermatozoa of fish (Lebistes reticulatus) were less sensitive than the spermatozoa of the mouse to the mutagenic effects of ionizing radiation. Newcombe and McGregor [19] predicted that an acute dose of 26 rads would be required for sperm and eggs of rainbow trout to double the rate of malformations observed in controls. These doses are much greater than the chronic doses calculated for the organisms living in the effluents of a nuclear power station.

Very few studies have been carried out on the long-term effect of chronic low-level radiation on natural aquatic populations. A cytogenetic study was started in 1960 on the Chironomus (midge) larvae which live in White Oak Lake and White Oak Creek [20]. The frequency and kind of chromosome aberrations observed in the White Oak Creek population were compared with control populations. The calculated dose received by Chironomus larvae which inhabit the radioactive bottom sediment of White Oak Creek was 230 rads/year. From 1960 to 1962, a total of 692 larvae from the irradiated population were analyzed for chromosome aberrations. A comparison of the aberrations observed in the irradiated population with an analysis of 714 larvae from control populations,

showed that more aberrations were being produced in the irradiated populations. However, these aberrations did not persist or become established in the population and were eliminated rapidly by selection or genetic drift. Chromosomal polymorphism, which consisted primarily of three inversions, was the same in the irradiated and in the control populations [21].

The irradiated population was again analyzed for chromosome aberrations in 1970, or 40 to 50 generations later. Table 4 summarizes the previous and latest data on the frequency of aberrations and the dose received by the organisms. In 1970, no aberrations were detected in the White Oak Creek population except five endemic inversions, and these were the same inversions that had been observed previously. This population of Chironomus tentans has a considerable amount of inversion chromosomal polymorphism and an inversion may become established in a population and occur at a rather high frequency. In this case, three of the endemic inversions occur at frequencies ranging from 8 to 17%. After ten years, five of these endemic inversions still occurred in the population. One inversion which occurred at a very low frequency in 1960-1963 was not observed in the 1970 sample and may have been lost from the population.

The dose rate to the larvae decreased from 230 rads/year in 1960 to 57 rads/year in 1965 and to 11 rads/year in 1970. The yearly discharge of the radionuclides which contributed most of the dose to Chironomus (Cs^{137} , Co^{60} , Sr^{90} , and Ru^{106}) has decreased over the past few years. Likewise, the concentration of radionuclides in the bottom sediment is lower. Thus our previous conclusion that irradiation from radionuclides in the bottom sediment was producing chromosome aberrations in the population was thus substantiated since the occurrence of these aberrations decreased as the dose rate decreased.

Another possible effect that is not well documented and is of some concern is the genetic effect of accumulated radionuclides that are incorporated into the genetic material. Lee et al [22] using ^{32}P attempted to distinguish between mutations caused by the beta radiation dose and mutations induced by the transmutation and energy of recoil from the decay of ^{32}P to ^{32}S . In their study using mature sperm of Drosophila melanogaster, no significant change in chromosome breakage and recessive lethals was detected that could be attributed to transmutation and recoil energy. Other studies have been conducted where an effect greater than the beta radiation exposure was produced by incorporated ^{32}P .

Tritium, an isotope of hydrogen, is produced by the activation of lithium and boron and released to the environment by nuclear power stations under normal operation. Tritium is of concern because it has a long physical half-life (12.36) years and its continued production may lead to increased levels in the environment. Since most tritium released to the environment eventually becomes tritiated water, this nuclide could be incorporated into the genetic material. Woodward [23] points out the lack of experimental evidence to show that the incorporation of tritium from tritiated water can produce mutation in higher organisms. In one of the few studies with tritiated water Dewey et al [24] showed that chromosome aberrations were produced in hamster cells cultured in a media containing tritiated water. Studies

Table 4. Chromosome Aberrations in Irradiated and Nonirradiated Populations of Chironomus tentans

	1960-1963 White Oak Creek (irradiated)	1960-1963 Control Populations (nonirradiated)	1970 White Oak Creek (irradiated)
Number of larvae analyzed	692	714	247
Number of induced chromosome aberrations	11	0	0
Types of endemic inversions	6	6	5
Dose rate	1960-230 rads/yr 1965-57 rads/yr	background	11 rads/yr

with Chironomus riparius [25] cultured in different concentrations of tritiated water showed that the frequency of chromosome aberrations produced by incorporated tritium was approximately the same as the frequency produced by an equivalent dose of chronic gamma radiation.

Synergistic Effects of Radiation and Temperature

Organisms living in the effluents of nuclear power stations will be exposed to heated water as well as radioactive effluents. Some information is available on the combined effects of radiation exposure and increased temperature; however most of the information involves acute exposure to radiation. Several reports have demonstrated that the sensitivity of aquatic organisms to radiation increases with increased temperature. Radiation damage was increased at higher temperatures in Oryzias latipes [26]. A temperature increase of 5°C significantly lowered the lethal dose to 50% of the fish in 30 days [LD₅₀(30)] to Gambusia [27]. Angelovic et al. [28] studied the interaction of temperature and salinity on the LD₅₀ of Fundulus heteroclitus and found that temperature affected the LD₅₀ more than salinity did over the range of the two factors tested. Gros et al. [29] found that survival of Carassius carassius after radiation was much greater at 7°C than at 25°C. In general these studies agree with the concept that radiation damage appears in a shorter time at higher temperatures due to increased metabolic processes.

The effect of radiation on the reproductive processes increased with increased temperatures. Rayera [30,31] shows that at higher temperature the effect of radiation on the reproductive process of adult snails was greater than at lower temperatures. The effect of chronic irradiation on reproduction in the snail, Physa heterostrophica, was less at 15°C than at 25°C [10]. A significant decrease in both capsule and egg production was demonstrated at 1, 2, and 5 rads/hour; at 15°C a significant decrease was found only at 5 rads/hour. Wadley and Welander [32] investigated the combined effects of X rays and temperature on mortality and growth of the chinook salmon (Oncorhynchus tshawytscha). Eggs which had been irradiated at four different stages of development were maintained at ambient temperature and 2°C above ambient. Although the elevated temperature resulted in greater mortalities, the effects were independent of dose. In general these studies support the hypothesis that aquatic organisms are more sensitive to radiation at higher temperatures.

Conclusion

This report is not intended to present a complete literature review. However, the information presented and other reviews (Auerbach et al. 1971 [33] and Templeton et al. 1970 [34]) support the conclusion that radiation levels as low as those calculated for biota in the vicinity of nuclear power stations (less than 1 rad/year) probably will not have a detectable or significant effect on aquatic biota.

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