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Dose Estimation and Prediction of Radiation Effects on Aquatic Biota Resulting from Radioactive Releases from the Nuclear Fuel Cycle*

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ABSTRACT

Aquatic organisms are exposed to radionuclides released to the environment during various steps of the nuclear fuel cycle. Routine releases from these processes are limited in compliance with technical specifications, requirements of federal regulations. These regulations reflect I.C.R.P. recommendations which are designed to provide an environment considered safe for man. It is generally accepted that aquatic organisms will not receive damaging external radiation doses in such environments; however, because of possible bioaccumulation of radionuclides there is concern that aquatic organisms might be adversely affected by internal doses. The objectives of this paper are: (1) to estimate the radiation dose received by aquatic biota from the different processes and determine the major dose-contributing radionuclides, and (2) to assess the impact of estimated doses on aquatic biota.

Dose estimates are made by using radionuclide concentration measured in the liquid effluents of representative facilities. Where measurements of concentrations are not available, predicted radioactive releases to the aquatic environment are used for dose calculations. Although radioactive releases from reactors used to generate electrical energy have received the most attention, and are the best documented, this evaluation indicates the potential for a greater radiation dose to aquatic biota from the nuclear fuel supply facilities (i.e., mining and milling).

The effects of chronic low-level radiation on aquatic organisms are discussed from somatic and genetic viewpoints. Based on the body of radiobiological evidence accumulated up to the present time, no significant deleterious effects are predicted for populations of aquatic organisms exposed to the estimated dose rates resulting from routine releases from conversion, enrichment, fabrication, reactors and reprocessing facilities. At the doses estimated for milling and mining operations it would be difficult to detect radiation effects on aquatic populations; however, the significance of such radiation exposures to aquatic populations cannot be fully evaluated without further research on effects of chronic low-level radiation.

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Introduction

Aquatic organisms are exposed to many different radionuclides released to the environment from various facilities of the nuclear fuel cycle. Routine releases from these processes are restricted in compliance with the International Commission on Radiological Protection (I.C.R.P.) which recommends limits for radiation doses for members of the general public [1]. These ICRP recommendations are designed to provide assurances that man-made environmental radioactivity does not exceed levels considered safe for man. It is generally accepted that aquatic organisms will not receive damaging external radiation doses in such environments; however, because of possible bioaccumulation of radionuclides there is concern that aquatic organisms might be adversely affected by internal doses.

This paper will address the effect on aquatic biota of radioactive releases from the different processes in the enriched uranium dioxide fuel cycle. Specific objectives are: (1) to estimate the radiation doses received by aquatic biota from the different process effluents and determine the major dose contributing radionuclides, and (2) to assess the impact of estimated doses on aquatic biota.

The different processes of the nuclear fuel cycle considered here are: uranium mining, uranium milling, conversion facilities, uranium enrichment, fuel fabrication, light water reactors and fuel reprocessing.

Model Facilities

In predicting radioactive releases to the aquatic environment, model facilities were assumed for the different processes in the nuclear fuel cycle. The models represent the methods most commonly used in the United States and the size of the facility is representative of the average facility. When possible, actual measurements of radionuclide concentrations in the liquid effluents were used as the source term for calculating the radiation dose rate to aquatic biota. The measurements were scaled to represent the liquid effluents from a model facility.

Dose Calculations

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

The BIORAD [2] computer code was used to calculate internal and external radiation doses to aquatic biota. For dose calculations it was assumed that the radionuclide concentrations in water remain constant and that the biota reach a steady-state concentration.

The effective absorbed energy used in the calculation of internal dose from each photon-emitting radionuclide is a function of the size of the organism. A conservative approach has been used because all BIORAD calculations of internal dose to aquatic plants, invertebrates, and fish have utilized effective absorbed energies for 30-cm diameter tissues. In almost all cases the effective diameter of aquatic biota is less than 30 cm; however, effective absorbed energies corresponding to this large diameter were chosen because they maximize the dose from gamma photons and x-rays. This conservative allocation is a safeguard against the possibility that the bioaccumulation factor or the radiosensitivity has been underestimated for a certain type of organism.

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 generally contribute the major part of the dose to the organisms. The bioaccumulation factors [3-5] used in the dose calculations for aquatic plants, invertebrates and fish represent the higher values found in the literature except for a few radionuclides for which existing data support smaller values than the highest found. In actual exposure situations, the accumulation of radionuclides is expected to be small because of dietary dilutions by noncontaminated foods or because of consumption of aquatic plants with bioaccumulation factors lower than those assumed.

Uranium Mining

About half of the uranium ore in the United States is produced by open pit (strip) mining [6]. The model mine complex occupies about 3000 acres and produces about 1600 MT ore per day [7]. This amount is equivalent to about 5.3 times the annual fuel requirement for a model light water reactor (1000 MWe). The liquid effluents from a mining operation consist of runoff from mining water which is pumped from the mine to keep it dry while the ore is extracted.

The drainage water contains relatively large amounts of suspended solids and is passed to a settling basin. Part of the water becomes run off, but the bulk recycles through natural seepage and evaporation. The run off contains natural uranium, radium, thorium and other radionuclides. When it is economically feasible, the uranium is recovered from the drainage water before it is discharged.

The assumption was made that the model mine pumped 1500 gpm of drainage water into a settling basin and that ten percent (150 gpm) was discharged as run off. Since most uranium mines in the United States are located in the arid southwest, the receiving habitat was assumed to be a small stream. The concentrations of radionuclides in Table I were obtained by diluting measured concentrations of radionuclides in mining water [7] in a 5 cfs (140 ℓ/s) stream.

Internal dose rate calculations for aquatic plants, invertebrates, and fish showed that Ra-226 and PO-210 were the greatest dose contributing radionuclides. Aquatic invertebrates received the greatest dose, 97 rads/yr from Po-210. This was due to the bioaccumulation factor of 2×10^4 which was used in the dose calculations. The water immersion dose to the biota exposed to radionuclides in the mining water was 0.017 mrad/yr for the gamma dose and 0.21 mrad/yr for the beta plus gamma dose.

Uranium Milling

Uranium mills extract U_3O_8 from ores which contain from four to six lbs. of uranium per ton. Extraction is accomplished by leaching crushed and ground ore with either an acid or alkaline solution. The acid leach process, which is the most commonly used, accounts for 80% of the annual production of U_3O_8 in the United States. After the ore is leached the resultant solution containing uranium goes through a solvent-extraction process in which the uranium is purified and concentrated. The residual (tailings) which represents the crushed ore minus most of the uranium is released as a slurry into a tailings pond.

The model uranium mill is located near a uranium mine and processes 600,000 MT of ore/yr. IT releases 2,500 MT/day of waste liquid into a tailing retention pond system. The retention system will permit the evaporation of most of the waste liquid; however, it is expected that there will be some seepage from the retention pond. Assuming a seepage rate of 300 ℓ/m (80 gpm), the estimated concentrations of radionuclides in a 5 cfs (140 ℓ/s) steam are given in Table 2 [8].

The resulting internal dose calculations to aquatic biota show that ^{230}Th and ^{226}Ra are the greatest dose contributors. Thorium-230 is released in the highest concentration in the seepage water and has a bioaccumulation of 1.5×10^3 in aquatic plants. As a result, aquatic plants receive the highest total dose, 1200 rads/yr.

Conversion Facilities - Uranium Hexafluoride Production

The next step in the nuclear fuel cycle is the conversion of the solid U_3O_8 from mills into the volatile uranium hexafluoride (UF_6) for subsequent isotopic enrichment. Two processes are used for UF_6 production: the dry hydrofluor method and the wet-solvent-extraction methods. Both processes are used to produce almost equal portions of total UF_6 in the United States. The hydrofluor method releases radioactivity primarily in the gaseous and solid states, while the solvent extraction method releases more of the radioactive waste in liquid effluents.

Since the wet-solvent-extraction method releases more radioactivity to the aquatic environment, this method was selected for use in the model plant. The model plant processes about 5000 MTU and is capable of supplying the annual fuel requirements of 27.5 model light water reactors [6]. A UF_6 plant uses large quantities of water for chemical processes and cooling systems. Therefore, it must be located near a reliable water source, such as a river or lake. The assumption was made that the model plant is located on a 1300 cfs (36.8×10^3 ℓ/s) river.

Irradiated materials are not handled by conversion facilities, and all radionuclides present in the liquid effluents occur, to some extent, in nature. The concentrations of radionuclides measured in the liquid effluent from a conversion plant [9] were used to obtain the radioactive source terms in Table 3. The assumption was made that 1125 gals/min (31.8×10^3 ℓ/s) were discharged into a 1300 cfs stream.

The total internal dose rate calculated for aquatic plants was 1.40 rads/yr and 0.14 rads/yr for aquatic invertebrates. The major dose-contributing radionuclides were uranium-234, 235 and 238.

Isotopic (Uranium) Enrichment

The concentration of U-235 is about 0.7% in the UF_6 produced in the conversion plants. The U-235 must be enriched to 2 to 4 percent before fuel can be fabricated. Enrichment is accomplished in a process called gaseous diffusion which involves some 1700 process stages.

The model plant produces 10,500 metric tons of separate work units per year, enought to furnish the annual fuel for 90 model light-water reactors of 1000 MW [6]. The plant must be located in an area where large quantities of cooling water are available. Radionuclides are released in liquid wastes from process cleanup operations and from auxiliary production facilities. The radionuclide concentrations in Table 4 represent the measured concentrations in the liquid effluents from the Oak Ridge Gaseous Diffusion Plant after discharge into a 1300 cfs stream.

Uranium-234 was the major dose contributing radionuclide with aquatic plants receiving the highest dose, 1.7 rads/yr.

Fuel Fabrication

Fuel fabrication plants convert UF_6 to UO_2 by a wet process in which ammonium hydroxide is reacted with steamed UF_6 to produce a slurry, which is then dried and converted to UO_2 powder. This powder is then compacted into pellets for placement in cladding to form fuel rods.

The model fuel fabrication plant produces 900 MT of fuel per year. This annual production will furnish the yearly requirements of 26 light-water reactors. The plant required about 425,000 gal/day of water which is used for cooling process equipment and diluting liquid process wastes prior to release. It is assumed that liquid effluents are released to a freshwater river which has a minimum flow of 1300 cfs. Table 5 gives the concentrations of radionuclides in the river and the radiation dose to aquatic biota [10]. Uranium 234 and 238 are important contributors to dose.

Light Water Reactors

Fuel elements are used in reactors to furnish heat for steam electric power plants for the generation of electricity. Over 50 nuclear power plants are currently in operation in the United States, and approximately 60 more are under construction. The model light water reactor produces a 1000 MW of electricity and requires 35 metric tons of UO_2 fuel per year to operate.

During the operation of nuclear power reactors, radionuclides are formed by fission of the nuclear fuel and by neutron activation of structural materials, corrosion products, and impurities in reactor coolant water. A small fraction of these radioactive materials enter the plant's waste system and are channeled into various effluent streams.

The concentration of radionuclides used in calculating doses to aquatic biota living in the vicinity of a nuclear power station are given in Table 6 for pressurized water reactors (PWR's) and in Table 7 for boiling water reactors (BWR's). The radionuclide concentration was obtained by taking the highest average annual concentration of each radionuclide measured in the effluents of ten pressurized water reactors and nine boiling water reactors [11]. The specific radionuclides in effluents vary from plant to plant because of fuel performance, reactor power production, and different designs in reactor and waste treatment systems. Therefore all of the radionuclides listed in Table 6 and Table 7 would not be found in the effluents of all reactors. Kaye and Rohwer [12] listed 89 radionuclides which were most often considered in environmental impact statements for light water reactors; however, only 28 radionuclides were identified in the effluents of pressurized water reactors and 23 in the effluents of boiling water reactors [11].

Dose calculations were based on the concentrations of radionuclides in the effluents. Although 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.

Nuclear reactors are located on fresh water streams, estuaries and open sea coasts; thus radioactive liquid effluents are released into saline as well as freshwater aquatic habitats. Consequently, dose rates were calculated for aquatic biota exposed to radioactivity in saline and freshwater for PWR's and BWR's, Table 6 and 7. Dose rates to aquatic biota in saline water were greater for algae and mollusks/crustaceans than for aquatic plants and invertebrates in fresh water as a result of higher bioaccumulation factors; however dose rates were greater for fish in fresh water. The isotopes of iodine are more important dose contributors in saline water than in fresh water because of the difference in bioaccumulation. Cobalt-60 and ^{54}Mn, which have relatively high bioaccumulation factors, are important dose contributors in both fresh and saline water. In comparing dose-contributing radionuclides from BWR's and PWR's, the isotopes of cesium (^{134}Cs and ^{137}Cs) are of greater importance in the effluents of PWR's as a result of decreased releases of other radionuclides. Conversely, the release of tritium in the liquid effluents of PWR's is about an order of magnitude higher; however, because of bioaccumulation of 1.0 and a low dose rate factor, tritium is not an important dose contributor.

Fuel Reprocessing

Spent fuel from a light-water reactor still contains usable fissonable material. Fuel reprocessing recovers this unused material by separating it from the radioactive product in spent portions. This reclaimed fuel is then cycled back to an enrichment plant and incorporated into new feed material for fuel fabrication.

In fuel reprocessing a mechanical shear and nitric acid leach system is used to segment and dissolve fuel elements. The unused portion of fuel is then purified and recovered by a solvent extraction method. The purified uranium product is converted to UF_6 and shipped to isotopic enrichment facilities. The residue from these processes is highly radioactive. Most of the fission products and transuranic elements built up in the fuel elements, which power light-water reactors, are now waste products of the reprocessing facility.

One commercial reprocessing plant has been in operation in the United States for about six years. This plant is currently shut down for extensive modification. An additional plant is under construction and is nearing completion [7].

The model plant will process 1500 metric tons of fuel per year and has no radioactive liquid effluent. However, it was assumed that radioactive materials from the gaseous effluents would be deposited in a fresh water river at the same rates and amounts as on a similar area of land [13]. To evaluate aquatic pathways leading to a potential radiation dose to aquatic biota, it was assumed that a segment of a river 1 mile long by 0.1 mile wide by 3 m deep is located 0.5 miles from a model plant in the direction of the prevailing wind. All radionuclides remain in the water at a steady state with no further dilution by volume flow or settling out.

The concentration of radionuclides in the water and the radiation dose to aquatic invertebrates and fish are given in Table 8. In general, dose to algae and invertebrate is due primarily to radionuclides of Cm, Ru, Cs and Y. The dose to fish is heavily influenced by radionuclides of Cs, Cm, and Nb. Algae receive the greatest dose because of bioaccumulation factors.

Effects of Radioactive Effluents on Aquatic Biota

Potential exposure to radiation from radionuclide concentrations which may result from releases from nuclear facilities was estimated in the previous sections. This section will attempt to assess the effects of radiation dose on aquatic biota from these releases. There is a lack of radiation effects information on aquatic biota; also in most cases the radiation dose in experimental work is orders of magnitude higher than that experienced by natural populations exposed to effluents from nuclear facilities. Thus extrapolation from controlled laboratory experiments will be necessary.

The effects of radiation on aquatic biota have been reviewed by Templeton et al. [14] and Auerbach et al. [15]. More recently a comprehensive review has been completed by Opehl et al. [16]. In general these reviews indicate that radiation effects would not be detected at the dose rates estimated for aquatic biota living in the effluents released from most nuclear facilities. With the exception of milling and mining operations most dose rates are estimated to be less than 30 rads per year.

In estimating doses from milling and mining operations a conservative approach was taken (i.e. the upper limits for bioaccumulation factors and radionuclide concentrations were used in dose estimations). Thus, the doses are upper limits or overestimates. The highest dose rates were estimated for aquatic biota receiving effluents from milling operations. Aquatic plants were estimated as receiving the highest doses, 1200 rads/yr, with aquatic invertebrates

receiving 360 rads/yr and fish 22 rads/yr, Table 2. The next highest annual dose was received by aquatic invertebrates (100 rads/yr) from mining water run-off. Habitats in which such doses occur should be in the restricted zone of the facility and considered part of the radioactive waste disposal system. Nevertheless, one can examine the effects of chronic irradiation on aquatic biota receiving equivalent dose rates.

The highest estimated radiation dose to plants (1200 rad/yr) would be expected to produce little or no measurable effects. Lower plants such as algae have a relatively high degree of radioresistance compared to higher plants. Chronic dose rates in the range of 3 to 4 rads/day have been shown to have effects on radiosensitive higher plants such as conifers but, at most, only slight growth-inhibiting effects [17].

Most of the studies which have been made on natural populations exposed to chronic radiation higher than background levels have been conducted at the Oak Ridge National Laboratory (ORNL). Studies have been conducted on populations of fish, snails, and insects that inhabit White Oak Lake. This lake, located in the ORNL reservation, has served as a final settling basin for low-level radioactive effluent since 1943 [18]. The natural populations which live in this environment have been exposed to chronic radiation for many generations. Gambusia affinis, the mosquito fish, which received an estimated dose of 11 rads/day had a significantly greater number of dead embryos and abnormal embryos than did control populations [19].

In related laboratory experiments the effects of chronic irradiation at dose rates of 1.3, 2.5 and 5.4 rads/hr were investigated for a period of 47 days [20]. No excessive mortality occurred at any of the doses. After 47 days the surviving fish were sacrificed for pathological studies. No histological effects were detected in the hemopoietic organs; however, atrophy of the testis was detected after 18 days at all dose rates including dose rates of 1.3 rad/hr. Based on the results of these experiments it would be exceedingly difficult to detect these types of results on fish that were exposed to chronic irradiation at a dose rate of 22 rads/yr, (100 mrads/day) the highest estimated dose rates for fish from any of the nuclear facilities.

Field and laboratory studies were conducted on the snail, Physa heterostropha, from White Oak Lake [21,22]. The dose rate 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 dose rates in the past. A larger number of eggs per capsule was observed in snails from White Oak Lake, but a decrease in the number of capsules per snail occurred. A series of laboratory experiments were conducted to determine the effects of 1, 10 and 25 rads/hour on survival size and reproduction of P. heterostropha. A dose rate of 1 rad/hr (8760 rads/yr) produced no significant effects while a dose rate of 10 rads/hr affected all parameters tested.

This section is not intended to be a review of the literature on the effects of radiation on aquatic biota, but the previous examples are representative. Based on these studies and on the previously mentioned reviews [14,15,16], it would be exceedingly difficult to detect somatic or reproductive effects on aquatic populations receiving a dose of 1 rad/day or less.

The problem of genetic effects of chronic low-level radiation cannot be dismissed. 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 rates. 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 [23,24]. The frequency and kind of chromosome aberrations observed in the White Oak Lake population were compared with control populations. The calculated dose received by Chironomus larvae in the White Oak Lake population was 230 rads/yr. More chromosome aberrations were being produced in the irradiated populations than in the control populations. However, these aberrations did not persist or become established in the population and were eliminated by selection or genetic drift. Similar effects would be expected in aquatic populations exposed to mining and milling effluents, but the significance of these effects on aquatic populations is difficult to assess.

The effects of an increased mutation rate on aquatic organisms has recently been addressed by Templeton et al. [25]. The argument was put forth that any prediction of the effects of an increased mutation rate on fish and other aquatic organisms resulting from an increase in the levels of environmental radiation must be made within the perspectives of the reproductive rate of the species and the value of one individual to the population. The same criteria cannot be used to assess and evaluate the consequences of an increased mutation rate for aquatic populations as are used for human populations. For humans, a great value is placed on the individual members and many individuals with relatively low adaptive values are maintained in the population. On the contrary, for aquatic organisms whose reproductive rates are generally very high and on which the selective pressures are strong, the value of one or even thousands of individual organisms to the population is rather insignificant insofar as the long-term structure and fate of the population are concerned. In such populations, often much less than one percent of the viable zygotes are normally expected to mature to adulthood and to reproduce, i.e., to comprise the effective gene-pool. Even if we make the most conservative assumption that all induced mutations are harmful to the population, we would predict that, even so, no significant deleterious effects are likely to be produced on populations of aquatic organisms at the dose rates estimated for all the nuclear facilities related to the nuclear fuel cycle with the exception of milling and mining operations.

Conclusion

The potential for greater radiation doses to aquatic biota seems to be associated with the nuclear fuel supply facilities (i.e. mining and milling). The higher doses are due to naturally occurring radionuclides, ^{226}Ra, ^{210}Po and ^{230}Th. This evaluation of dose to aquatic organisms supports the increased attention now being given to environmental problems related to the final disposition of radioactive wastes such as mill tailings, which contain uranium and its daughter radionuclides. Because of the number, the importance, and the production of fission radionuclides, radioactive releases from nuclear power plants have received the most public attention. The nuclear reactors are also the best

monitored facilities; however, on a comparative basis, the radiation dose estimated for aquatic biota in the effluent of a nuclear power reactor is less than for most of the other facilities.

The dose rate estimates are conservative and are probably overestimates of the doses received by aquatic biota from radioactive releases from the different facilities of the nuclear fuel cycle.

In conclusion we would predict that somatic or genetic effects produced on aquatic biota at the dose rates estimated for conversion, enrichment, fuel fabrication, nuclear power reactors, and reprocessing facilities would not significantly affect the exposed aquatic populations. Dose rate estimates for aquatic biota from milling and mining operations are much higher than estimates from other facilities in the nuclear fuel cycle. Additional information from long-term studies on aquatic populations exposed to chronic low-level irradiation would be necessary to fully evaluate the effects of such dose estimates. However, even at these higher dose rates (aquatic plants, 3.3 rads/day, invertebrates 1 rad/day and fish 0.06 rad/day) based on the information now available, radiation effects on aquatic populations probably would not be detected and the populations would continue without obvious detrimental effects.

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TABLE I

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Model Uranium Mining Operation

Radionuclides	Microcurie/ml	Aquatic Plants	Invertebrates	Fish
U-234	5.3E-09[a]	4.9E+03	4.9E+02	4.9E+01
U-235	5.3E-09	4.6E+03	4.6E+02	4.6E+01
U-238	5.3E-09	4.3E+03	4.3E+02	4.3E+01
RA-226	7.4E-09	3.8E+04	3.8E+03	7.6E+02
TH-230	1.3E-09	1.8E+03	5.8E+02	3.5E+01
PB-210	3.3E-10	1.2E+01	6.2E_00	1.9E+01
PO-210	4.7E-09	9.7E+03	9.7E+04	2.4E+02
TOT DOSE		6.3E+04	1.0E+05	1.2E+03

[a]Read as 5.3×10^{-9}.

TABLE II

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Model Uranium Milling Operation

Radionuclides	Microcurie/ml	Aquatic Plants	Invertebrates	Fish
U-234	9.6E-09[a]	8.8E+03	8.8E+02	8.8E+01
U-235	9.6E-09	8.3E+03	8.3E+02	8.3E+01
U-238	9,6E-09	7.7E+03	7.7E+02	7.7E+01
TH-230	7.9E-07	1.1E+06	3.5E+05	2.1E+04
RA-225	1.3E-09	6.7E+04	6.7E+03	1.3E+03
TOT DOSE		1.2E+06	3.5E+05	2.2E+04

[a]Read as 9.6×10^{-9}.

TABLE III

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Model Conversion Facility

Radionuclides	Microcurie/ml	Aquatic Plants	Invertebrates	Fish
U-234	5.4E-10[a]	4.9E+02	4.9E+01	4.9E+00
U-235	5.4E-10	4.6E+02	4.6E+01	4.6E+00
U-238	5.4E-10	4.3E+02	4.3E+01	4.3E+00
RA-226	9.6E-13	4.9E+00	4.9E-01	9.9E-02
TH-230	3.8E-13	5.1E-01	1.7E-01	1.0E-02
TOT DOSE		1.4E+03	1.4E+02	1.4E+01

[a]Read as 5.4×10^{-10}.

TABLE IV

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Model Uranium Enrichment Facility

Radionuclide	Concentration (μCi/ml)	Algae	Invertebrates	Fish
To-99	1.6E-8[a]	1.1E0[b]	1.4E-1	4.2E-1
U-234	1.2E-9	1.1E3	1.1E2	1.1E1
U-235	5.6E-11	4.8E1	4.8E0	4.8E-1
U-236	1.7E-11	1.5E1	1.5E0	1.5E-1
U-238	7.1E-10	5.7E2	5.7E1	5.7E0
Total		1.7E3	1.7E2	1.8E1

[a]Read as 1.6×10^{-8}.

[b]Read as 1.1.

TABLE V

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Model Fuel Fabrication Facility

Radionuclide	Microcurie/ml	mrad/yr			
		Plants	Invertebrates	Fish	Waterfowl
U-238	9.53E-8[a]	1.03E+0	1.24E+2	2.07E+1	2.07E-1
U-235	3.35E-9	3.37E-2	4.04E+0	6.73E-1	6.69E-2
U-236	4.85E-9	5.00E-2	6.01E+0	1.00E+0	1.00E-2
U-238	1.85E-8	1.75E-1	2.09E+1	3.49E+0	3.49E-2
Th-271	3.35E-9	3.98E-1	1.33E-1	7.95E-3	3.72E-6
Th-234 & Pa-234	1.85E-8	1.09E+1	3.69E-1	2.22E-1	3.92E-3
Total		1.28E+1	1.58E+2	2.61E+1	2.62E-1

[a]Read as 1.6×10^{-8}.

TABLE VI

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Pressurized Water Reactor Fresh Water and Saline Water Habitats

		Fresh Water			Saline Water		
Radio-nuclides	Micro-curie/ml	Aquatic Plants	Inverte-brates	Fish	Algae	Mollusks/ Crustaceans	Fish
H-3	7.6E-06[a]	1.4E+00	1.4E+00	1.4E+00	1.4E+00	1.4E-00	1.4E+00
C-14	1.1E-10	4.9E-01	9.7E-01	4.9E-01	1.1E-04	1.1E-04	1.1E-04
NA-24	2.7E-09	1.3E+01	2.3E+00	2.7E+00	1.3E-01	1.3E-01	1.3E-01
MN-54	8.4E-12	8.0E-01	3.2E+00	8.0E-03	8.0E-01	4.0E+00	2.4E-01
CR-51	3.5E-09	6.5E-02	3.2E-02	6.5E-02	1.6E+00	1.6E+00	1.6E-01
FE-59	2.8E-10	4.2E+00	1.4E+01	4.2E-01	2.5E+01	8.5E+01	4.2E+00
CU-64	1.7E-11	7.7E-02	7.7E-02	1.5E-02	7.7E-02	3.9E-01	7.7E-02
CO-57	4.9E-12	1.6E-03	1.6E-03	1.6E-04	8.2E-04	8.2E-02	8.2E-04
CO-58	4.0E-09	9.0E+00	9.0E+00	9.0E-01	4.5E+00	4.5E+00	4.5E+00
CO-60	2.5E-09	1.4E+01	1.4E+00	7.7E-01	7.7E-01	3.8E+01	3.8E+00
ZN-65	1.3E-10	7.7E-01	7.7E+00	7.7E-01	7.7E-01	3.8E+01	3.8E+00
SR-89	4.2E-11	2.1E-01	4.3E-02	2.1E-03	8.5E-03	4.3E-04	4.3E-04
SR-90	2.6E-12	2.7E-02	5.3E-03	2.7E-04	1.1E-03	5.6E-05	5.3E-05
NB-95	1.6E-10	1.2E+00	1.5E-01	4.6E+01	1.5E-01	3.1E-01	1.5E-01
ZR-95	4.0E-11	8.2E-01	5.5E-03	2.7E-03	8.2E-01	8.2E-02	2.5E-02
MO-99	1.2E-10	1.2E+00	1.2E-02	1.2E-02	1.2E-01	1.2E-01	1.2E-02
RU-106	3.9E-10	2.1E+00	3.1E+00	1.0E-01	1.0E+01	1.0E+00	3.1E-02
AG-100M	4.6E-13	2.9E-03	1.1E-02	3.3E-05	1.4E-02	7.2E-02	1.4E-02
SB-124	1.1E-11	5.2E-01	3.4E-03	3.4E-04	3.4E+00	3.4E-01	3.4E-01
I-131	3.9E-09	1.3E+00	1.6E-01	4.9E-01	3.2E+02	3.2E+00	6.5E-01
I-132	5.7E-11	7.2E-02	9.0E-03	2.7E-02	1.8E+01	1.8E-01	3.6E-02
I-133	7.2E-09	4.5E+00	5.6E-01	1.7E+00	1.1E+03	1.1E+01	2.2E+00
I-134	1.5E-08	1.7E+01	2.1E+00	6.3E+00	4.2E+03	4.2E+01	8.4E+00
I-135	5.0E-09	4.8E+00	6.0E-01	1.8E+00	1.2E+03	1.2E+01	2.4E+00
CS-134	5.3E-14	8.7E-05	1.1E-04	4.8E-04	1.1E-05	5.4E-05	3.3E-05
Cs-137	1.3E-08	1.1E+01	1.4E+01	5.7E+01	1.4E+00	7.2E+00	4.3E+00
LA-140	4.2E-12	7.5E-01	1.5E-01	3.7E-03	4.5E-02	1.5E-02	4.5E-03
CE-144	2.9E-10	3.6E+01	7.1E+00	1.8E-01	2.1E+00	7.1E-01	2.1E-01
W-187	1.0E-12	1.5E-02	1.3E-04	1.5E-02	1.3E-03	1.3E-03	1.3E-04
TOT DOSE		1.2E+02	7.9E+01	1.2E+02	6.9E+03	1.4E+03	3.9E+01

[a]Read as 7.6×10^{-6}.

TABLE VII

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Boiling Water Reactor in Fresh Water and Saline Water Habitats

Radio-nuclides	Micro-curie/ml	Fresh Water			Saline Water		
		Aquatic Plants	Inverte-brates	Fish	Algae	Mollusks/ Crustaceans	Fish
H-3	3.6E-07[a]	6.8E-02	6.8E-02	6.8E-02	6.8E-02	6.8E-02	6.8E-02
NA-24	1.2E-09	6.0E+00	1.0E+00	1.2E+00	6.0E-02	6.0E-02	6.0E-02
MN-54	1.1E-08	1.0E+03	4.0E+03	1.0E+01	1.0E+03	5.0E+03	3.0E+02
CR-51	2.8E-08	5.1E-01	2.6E-01	5.1E-01	1.8E+01	1.3E+01	1.3E+00
FE-59	1.8E-10	2.7E+00	8.6E+00	2.7E-01	1.6E+01	5.4E+01	2.7E+00
CU-64	2.2E-10	1.0E+00	1.0E+00	2.1E-01	1.0E+00	5.2E+00	1.0E+00
CO-58	2.2E-09	5.0E+00	5.0E+00	4.0E-01	2.5E+00	2.5E+02	2.5E+00
CO-60	8.2E-08	4.6E+02	4.6E+02	4.6E+01	2.3E+02	2.3E+04	2.3E+02
ZN-65	1.1E-09	6.4E+00	6.4E+01	6.4E+00	6.4E+00	3.2E+02	3.2E+01
SR-89	2.1E-09	1.1E+01	2.2E+00	1.1E-01	4.3E-01	2.2E-02	2.2E-02
SR-90	3.5E-10	3.6E+00	7.2E-01	3.6E-02	1.4E-01	7.2E-03	7.2E-03
Y-90	3.5E-10	2.9E+01	5.8E+00	1.5E-01	1.7E+00	5.8E-01	1.7E-01
MO-99	1.8E-09	1.8E+01	1.8E-01	1.8E-01	1.8E+00	1.8E+00	1.8E-01
SB-124	2.6E-10	1.2E+01	7.7E-02	7.7E-03	7.7E+01	7.7E+00	7.7E+00
I-131	1.8E-07	6.0E+01	7.5E+00	2.3E+01	1.5E+03	1.5E+01	3.0E+00
I-132	7.2E-12	9.2E-03	1.1E-03	3.4E-03	2.3E+00	2.3E-02	4.6E-03
I-133	1.4E-09	9.4E-01	1.2E-01	3.5E-01	2.4E+02	2.4E+00	4.7E-01
I-134	9.9E-13	1.1E-03	1.4E-04	4.2E-04	2.8E-01	2.8E-03	5.6E-04
CS-134	8.8E-09	1.4E+01	1.8E+01	7.2E+01	1.8E+00	9.1E+00	5.4E+00
CS-137	1.6E-08	1.4E+01	1.8E+01	7.1E+01	1.8E+00	8.9E+00	5.3E+00
LA-140	1.1E-09	2.0E+02	3.9E+01	9.9E-01	1.2E+01	3.9E+00	1.2E+00
N-187	5.4E-12	8.3E-02	6.9E-04	8.3E-02	6.9E-03	6.9E-03	6.9E-04
NP-239	1.5E-09	8.3E+00	3.3E+00	8.3E-02	4.0E-01	6.7E-01	6.7E-01
TOT DOSE		1.9E+03	4.6E+03	2.3E+02	3.1E+03	2.9E+04	5.9E+02

[a]Read as 3.6×10^{-7}.

TABLE VIII

Estimated Internal Dose to Aquatic Biota in mrads/yr from Radioactive Effluents from a Model Fuel Reprocessing Plant

Radionuclide	Concentration (μCi/ml)	Algae	Invertebrates	Fish
H-3	1.7E-07[a]	3.2E-02	3.2E-02	3.2E-02
I-129	1.2E-10	8.2E-03	1.0E-03	3.1E-03
I-131	3.0E-10	9.9E-02	1.2E-03	3.7E-02
RU-103	1.8E-10	3.0E+00	4.4E-01	1.5E-02
RU-106	9.8E-10	5.1E+01	7.7E+00	2.5E-01
CS-134	5.2E-10	5.3E+00	1.1E+00	4.2E+00
CS-137	2.6E-10	1.4E+00	2.8E-01	1.3E+00
TE-127m	1.4E-11	8.2E-02	8.2E-03	8.3E-04
TE-129m	5.7E-12	2.3E-02	1.2E-02	1.2E-03
SR-89	3.9E-11	2.0E-01	4.0E-02	2.0E-03
SR-90	3.7E-11	3.8E-01	7.7E-02	3.8E-03
Y-90	3.7E-11	3.1E+00	6.2E-01	1.6E-02
Y-91	7.2E-11	4.0E+00	7.9E-01	2.0E-02
ZN-95	1.2E-10	2.5E+00	1.7E-02	3.4E-03
NB-95	2.2E-10	1.7E+00	2.1E-01	6.4E+00
AG-110m	1.2E-12	7.5E-03	2.9E-02	6.7E-05
SB-125	3.9E-12	3.7E-02	2.4E-04	2.4E-05
CE-141	2.2E-11	3.4E-01	8.6E-02	2.2E-03
CE-144	3.7E-11	3.6E+00	9.0E-01	2.2E-02
PM-142	4.8E-11	3.1E-01	6.2E-02	1.5E-03
EU-154	3.3E-12	4.1E-01	8.1E-02	2.0E-03
EU-155	3.1E-12	4.6E-03	9.2E-04	2.3E-05
U-234	3.7E-14	1.7E-06	2.0E-04	3.4E-05
U-235	8.2E-17	3.5E-08	4.wE-06	7.1E-07
U-236	1.4E-15	6.1E-07	7.4E-05	1.2E-05
U-237	1.5E-15	6.2E-07	7.4E-05	1.2E-05
PU-238	3.4E-12	1.3E+00	3.7E-01	1.3E-02
PU-239	4.0E-13	1.4E-01	3.9E-02	1.4E-03
PU-240	5.7E-13	2.0E-01	5.6E-02	2.0E-03
PU-241	1.2E-10	1.8E+00	5.3E-01	1.8E-02
AM-241	7.7E-15	4.1E-03	8.2E-04	2.0E-05
AM-243	8.7E-15	4.4E-02	8.3E-03	2.2E-04
CM-242	8.2E-12	6.1E+01	1.2E+01	3.1E-01
CM-244	1.2E-12	6.7E+00	1.3E+00	3.3E-02
TOT DOSE		1.5E+02	2.7E+01	1.2E+01

[a]Read as 1.7×10^{-7}.