This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-76SR00001 with the U.S. Department of Energy.

radioactivity
effluent streams
fish
dose standard

DPST-86-620

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

CC: E. F. Ruppe, Wilm., M-6600
H. S. Eleuterio, M-6600
J. E. Conaway, M-6600
J. T. Granaghan, SRP, 703-A
J. A. Porter, 703-A
W. C. Reinig, 703-A
A. J. Garrett, 735-A
R. L. Kump, 735-A
C. C. Zeigler, 735-A
J. T. Lowe, SRL, 773-A
R. J. Guschl, 773-A
A. L. Boni, 773-A
SRL Publications (4)
E/T Chron File

August 20, 1986

TO: R. W. BENJAMIN, 773-A

FROM: W. L. MARTER WLMarter

PROPOSED RELEASE GUIDES TO PROTECT AQUATIC BIOTA

SUMMARY

The South Carolina Department of Health and Environmental Control requested DOE/SR to limit discharges of radioactivity to effluent streams to protect aquatic biota. At the request of DOE, the Savannah River Laboratory was assigned the task of developing the release guides.

A review of aquatic radioecology literature by two leading experts in the field of radioecology concludes that exposure of aquatic biota at one rad per day or less will not produce detectable deleterious effects on aquatic organisms. On the basis of this report, the Department of Energy recommends the use of one rad per day as an interim dose standard to protect aquatic biota.

Current releases of radioactivity to effluent streams results in biota doses much less than one rad per day. Since these releases reflect the ALARA (as low as reasonably achievable) principle in effluent management, it is recommended that there by no change in the current method of establishing release guides.

Release guides are reviewed annually and revised on the basis of projected operations for the forthcoming year. Before these guides are put into effect each year, it is recommended that dose calculations be made for aquatic biota with a computer model to ensure that the interim dose standard will not be exceeded. Since fish are the most radiosensitive form of biota in SRP streams, compliance with the proposed interim dose standard can be demonstrated with periodic calculation of fish doses based on radioanalyses of fish from critical stream locations.

BACKGROUND

In a letter from R. L. Morgan to G. F. Curtin on May 13, 1985[1], it was stated that the South Carolina Department of Health and Environmental Control (SCDHEC) requested the Department of Energy (DOE) to limit its radioactive discharges to streams to quantities that will not adversely affect the aquatic ecosystems. They indicated a strong desire to place this request into the National Pollution Discharge Elimination System (NPDES) permits. The Savannah River Operations Office agreed to establish such limits outside the permitting process and to work cooperatively with SCDHEC.

Reference 1 requested that DuPont develop a program for establishing interim water quality limits for discharges of radioactivity to surface waters on the SRP. This request was later placed in abeyance by DOE/SR pending the expected issue of an interim standard by DOE-HQ. Reference 2 reported adoption of a one rad per day dose limit to aquatic biota as an interim standard and requested that DuPont adopt controls to ensure that aquatic biota will not be exposed in excess of the standard.

RADIOSENSITIVITY OF AQUATIC ORGANISMS

Routine releases of radioactivity to liquid effluents are restricted to amounts which assure that environmental radioactivity does not exceed levels considered safe for man. Derived concentration guides for radioactivity in water in uncontrolled areas were developed by DOE such that an effective dose equivalent of 100 mrem is not exceeded when drinking 2 liters of water per day. Derived concentration guides for human consumption of water, based on an effective dose equivalent limit of 100 mrem, are listed in Reference 3.

It is generally accepted that the need to limit doses to man to low levels will ensure that doses to other organisms will not be large enough to cause ecological changes[4]. Because of possible bioaccumulation of radionuclides, however, there is concern that aquatic organisms might be adversely affected by internal doses.

At the request of the Assistant Secretary for Environment, Safety and Health, DOE-HQ, two leading experts in the field of aquatic radioecology were asked to review the literature on the effects of chronic radiation on aquatic biota in order to determine a dose limit which would protect aquatic organisms on DOE sites. In response to this request, B. G. Blaylock (ORNL) and W. L. Templeton (PNL) reviewed the literature and submitted a report to DOE (copy attached)[5]. The summary of their report follows:

"In summary, literature on radiation effects and methods for estimating the dose ot aquatic biota are available for predicting the effects of radioactive effluents from nuclear facilities on aquatic biota. It is generally accepted that exposure of aquatic biota at one rad per day or less will not produce detectable deleterious effects on populations of these organisms. However, at levels approaching one rad per day, additional supporting data would be desirable to definitively confirm the absence of detrimental effects on aquatic populations."

Based on the Blaylock-Templeton report, DOE-HQ suggested an interim guide of one rad per day for aquatic organisms while efforts are continued to adopt a standard which has input from additional members of the scientific community.

AQUATIC DOSIMETRY

Aquatic organisms receive external doses from radioactivity in water and sediment and internal doses from radionuclides concentrated internally either directly or through their food chains.

Three methods of calculating these doses were investigated. They were:

- IAEA method[6]
- BIORAD, a computer program developed by ORNL[7]
- CRITR, a computer program developed by PNL[8]

The IAEA method was perhaps the most sophisticated of the three methods. However, many of the parameters needed to calculate doses by this method were not available; also, a computer program was not available. The BIORAD and CRITR methods make use of much simplified, idealized models, in which the physical geometries of aquatic organisms are standardized. Aquatic organisms are of widely differing geometries, and in many cases, even the approximate geometry is unknown. Both of the methods assume standard geometries which sould be conservative, i.e., if dose calculational errors are made, the errors should result in overestimates of biota dose.

A comparison of dose estimates for aquatic biota for radionuclides typical of SRP discharges was made with the BIORAD and CRITR (LADTAP computer code) dose calculation methods. There was reasonable agreement in doses calculated by these methods as shown in Table 1. In this table, doses are shown for radionuclide concentrations in water equal to the DOE derived concentration guides for uncontrolled areas[3].

The CRITR method was selected for aquatic dose calculation at SRP because the method is incorporated in the LADTAP computer code[9,10] used at SRP for calculating dose to man from radionuclide releases to liquid effluents. The LADTAP code implements the models recommended by the U. S. Nuclear Regulatory Commission for assessing the effects of commercial nuclear power reactor operations[11].

In the LADTAP program, external doses to aquatic organisms from water and sediment are calculated with the same external dose factors as used for calculating dose to man from swimming and exposure to sediment, appropriately adjusted for exposure geometry and exposure time. Exposure times used in LADTAP are shown in Table 2.

Dose factors are provided which relate concentrations of radionuclides in sediment and water to external dose rate from penetrating radiation. External doses are usually insignificant compared with internal dose; nevertheless, external doses are calculated. The dose factors used for radionuclides normally released to SRP effluents are shown in Table 3.

Internal doses to aquatic organisms can be calculated directly from water concentrations, bioaccumulation factors, and effective energy imparted within the organism during radioactive decay. Aquatic organisms can concentrate radionuclides from their water environment either directly or via their food chains. The concentrations of radionculides in organisms can be related to concentrations in water by use of bioaccumulation factors. Bioaccumulation factors are the ratio of concentration per unit mass in the organism to concentration per unit mass in water after the organisms have come into equilibrium with their environment. In the LADTAP code, we use generic freshwater bioaccumulation factors for fish, invertebrates, and algae recommended by the NRC[11] for all elements except cesium: a SRP-specific bioaccumulation factor of 3000 for fish is used for cesium instead of the value of 2000 recommended by the NRC. The SRP-specific value for cesium is based on studies at SRP[12]. Bioaccumulation factors for elements normally released to SRP effluents are shown in Table 4.

The fraction of energy absorbed during decay of a specific radionuclide in an aquatic organism is a function of the effective radius of the organism, the type of radiation emitted (i.e., alpha, beta, and gamma), and the energy of the radiation emitted. In LADTAP, the effective radius of all aquatic organisms is taken to be 2 cm. In the case of alpha radiation, the volume of the organism is sufficiently large relative to the particle range that essentially all of the energy emitted is absorbed within the organism. For beta radiation, with ranges in unit density tissue up to 2 cm, a large fraction of the energy emitted is deposited within the organism. The absorption coefficient of tissue for gamma radiation is so low that only a small fraction of the energy emitted is deposited within the organism. All of these factors are taken into account when calculating the effective absorbed energy during radioactive decay. The effective energies incorporate quality factors used in ICRP 2[13] for calculating dose equivalent (rem dose) to man. Thus, for some radionuclide, the absorbed dose (rad dose) will be over-estimated. Examples of radionuclides for which absorbed dose will be overestimatd are low energy beta emitters (H-3) and alpha emitters (most actinides). The dose to an aquatic organism from a specific radionuclide i is calculated with the following equation:

$$\text{Dose, mrad per year} = \frac{20.93\ Q_i N_i B_i \varepsilon_i e^{-\lambda_i t}}{F}$$

Where

Q_i = release rate of nuclide i, Ci/year

N_i = reconcentration factor, dimensionless

B_i = bioaccumulation factor for nuclide i in organism, dimensionless

ε_i = effective energy of nuclide i in organism, MeV

λ_i = radiological decay constant for nuclide i, hr^{-1}

t = transit time for nuclides to reach point of exposure, hrs

F = flow rate of effluent, cubic feet per second

20.93 = proportionality constant

CALCULATED DOSES TO AQUATIC BIOTA IN SRP STREAMS

The transport of radionuclides in each plant stream in 1986 is shown in Table 6. This transport is the sum of 1986 release guides for direct releases to streams and indirect release via seepage basin migration and desorption of radioactivity from stream bed sediments in 1985. These transport data were used to calculate doses to aquatic biota.

The releases do not all occur at a single point within some stream systems. For example, in Four Mile Creek, radioactivity enters the stream in at least six locations, i.e., H-Area process water, H-Area seepage basin migration, burial ground migration, F-Area process water, F-Area seepage basin migration, and C-Area process water. Desorption of Cs-137 from sediments occurs over a long stretch of the stream. In order to reduce the number of calculations and simplify data presentation, aquatic doses were conservatively calculated as if the total transport of radioactivity in each creek occurred at a single location of lowest water flow (low dilution). If a stream has multiple entry points for radioactivity, the use of low flow results in an overestimate of aquatic biota dose. With this conservatism, aquatic doses were calculated with the LADTAP program and are shown in Table 7. In all cases, calculated doses to all biota are less than one rad per year.

The highest calculated biota doses in Table 7 are in Four Mile Creek and Pen Branch, i.e., algae dose of 583 mrad/year in Four Mile Creek and 359 mrad/year in Pen Branch. In Four Mile Creek, 52% of the fish dose of 378 mrad/year is from tritium; in Pen Branch, almost 100% of the fish dose of 305 mrad/year is from tritium. Under current operating conditions, thermal discharges from reactors prevent fish habitation in Four Mile Creek below SRP Road 3 and in most of Pen Branch.

FISH DOSES FROM MEASURED RADIOACTIVITY

A limited amount of radioanalytical data exists for fish from SRP streams. The data that is available for the 1980-1985 period is shown in Table 8. Analyses for H-3 and Sr-90 in fish from effluent streams were discontinued in 1981; Cs-137 analyses are available at the stream locations shown through 1985. The Sr-90 data in Table 8 represents concentrations in the skeleton of fish. Generally, Sr-90 concentrations in flesh of fish were less than the sensitivity of analysis.

The measured concentrations in fish in Table 8 were used to calculate doses to fish in SRP streams. The calculated doses for both average and maximum concentrations are shown in Table 9. However, only the doses from average concentrations are pertinent to this study because we are more concerned with population effects rather than with maximum individual effects. If bone dose from Sr-90 is disregarded and if the 1985 Cs-137 dose is combined with the 1980 tritium dose, all of the average total body doses shown are much less than the DOE interim guide of 365 rad per year (1 rad per day). This is in general agreement with aquatic doses as calculated with the LADTAP program on the basis of radioactivity transport (Table 7). Bone doses from Sr-90, particularly for fish from Four Mile Creek in 1980, are higher than total body doses. Even these higher bone doses are still well within the 365 rad per year (1 rad per day) proposed as an interim aquatic dose standard for fish.

COMPLIANCE WITH THE PROPOSED AQUATIC DOSE STANDARD

SRP can comply with the proposed interim dose standard of one rad per day for fish under current operating conditions. Currently, release guides are reviewed and revised annually based on projected operating conditions for the forthcoming year. It is proposed that this method of establishing release guides be continued. Before new release guides are put into effect, they should be summed for each stream with indirect releases, i.e., anticipated seepage basin migration and desorption of radioactivity from stream bed sediments, and be used to calculate aquatic doses with the LADTAP computer code to ensure that the interim dose standard will not be exceeded. Aquatic biota doses should be calculated for any releases that exceed the guides on an annual basis to determine if the interim dose standard will be exceeded. Any change in processes or new processes which will change the radionuclides or amounts of radioactivity released should be evaluated for dose to aquatic biota before the processes are started.

Doses as calculated with the LADTAP program are conservative and should be adequate to predict compliance with the proposed guides. However, routine monitoring of fish should be initiated in those locations in each stream where the combination of radioactivity transport and stream flow rate would lead to the maximum potential exposure of fish to ensure compliance with the interim aquatic dose standard. Only fish need be routinely monitored because they are the most radiosensitive form of biota in SRP streams. However, periodic spot checks on algae and invertebrates on some infrequent schedule to be determined would provide complete assurance of compliance.

WLM/jpr

REFERENCES

1. "Request to Develop Interim Water Quality Limits for Discharge of Radioactivity to Surface Waters of the Savannah River Plant (SRP)", letter to G. F. Curtain from R. L. Morgan (May 13, 1985).

2. "Interim Water Quality Standard for Radioactivity in Surface Water and Groundwater - -", letter to E. F. Ruppe from R. L. Morgan (July 3, 1986.)

3. Wright, S. R., "Derived Concentration Guides Applicable to Members of the Public for Radionuclides in Air and Water", letter to R. J. Guschl (May 7, 1986).

4. "Radionuclide Release into the Environment: Assessment of Dose to Man", ICRP Publication 29, International Commission on Radiological Protection, Annals of the ICRP, Pergamon Press (1978).

5. Blaylock, B. G. and W. L. Templeton, "A Review of the Effects of Radiation on Aquatic Organisms", a report to DOE-HQ (1986).

6. "Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems", Technical Report Series No. 172, International Atomic Energy Agency, Vienna (1976).

7. Killough, G. G. and L. R. McKay, "A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment", ORNL-4992, Oak Ridge National Laboratory (1976).

8. Final Environmental Impact Statement: Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low As Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents, Volume 2 of 3 volumes, WASH 1258, U. S. Atomic Energy Commission (1973).

9. Simpson, D. B. and Betty L. Mcgill, "Users Manual for LADTAP II - A Computer Program for Calculating Radiation Exposure to Man from Routine Releases of Nuclear Reactor Effluents", NUREG/CR-1276, prepared for the U. S. Nuclear Regulatory Commission by Oak Ridge National Laboratory (March, 1980).

10. Marter, W. L., "Environmental Dosimetry for Normal Operations at SRP", DPST-83-270, Rev. 1, Savannah River Laboratory (March 22, 1984).

11. Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10CFR50, Appendix I, Regulatory Guide 1.109, Rev. 1, U. S. Nuclear Regulatory Commission (October, 1977).

12. Gladden, J. B., "Cs-137 Concentration Factor for Savannah River Fish", memorandum to M. H. Smith, Savannah River Ecology Laboratory (February 12, 1982).

13. "Report of ICRP Committee II on Permissable Dose for Internal Radiation", ICRP Publication 2, International Commission on Radiological Protection, Health Physics, Vol. 3 (June, 1960).

Table 1
COMPARISON OF DOSES BY BIORAD AND LADTAP

Nuclide	Derived Conc. Guide, uCi/ml	BIORAD Dose, rad/year from Der. Conc. Guide			LADTAP Dose, rad/year from Der. Conc. Guide			Ratio BIORAD/LADTAP		
		Algae	Invert.	Fish	Algae	Invert.	Fish	Algae	Invert.	Fish
H-3(a)	2.0E-03	3.4E-01	3.4E-01	3.4E-01	3.4E-01	3.4E-01	3.4E-01	1.006	1.006	1.006
C-14	7.0E-05	3.2E+02	6.4E+02	3.2E+02	3.0E+02	6.0E+02	3.0E+02	1.060	1.070	1.060
Co-60	5.0E-06	2.8E+01	2.8E+01	7.2E+00	4.7E+00	2.5E+02	1.2E+02	6.022	0.113	0.059
Sr-90(a)	1.0E-06	1.0E+01	2.1E+00	6.0E-01	1.1E+01	2.1E+00	6.4E-01	0.935	0.981	0.935
Tc-99	1.0E-04	7.0E+00	8.8E-01	2.6E+00	6.3E+00	7.9E-01	2.4E+00	1.111	1.117	1.102
I-129(a)	5.0E-07	3.0E-02	4.0E-03	1.1E-02	1.8E-02	1.5E+00	7.4E-01	1.657	0.003	0.015
Cs-137(a)	3.0E-06	1.7E+01	3.3E+00	9.9E+01	7.6E+00	7.1E+01	8.0E+01	2.252	0.046	1.238
U-238(a)	6.0E-07	2.7E-01	2.9E+01	9.9E-01	2.4E-01	3.0E+01	1.2E+00	1.136	0.977	0.843
Pu-239(a)	3.0E-07	1.1E+02	3.0E+01	1.1E+00	1.0E+02	2.9E+01	1.0E+00	1.078	1.034	1.078

a. Radionuclides released to streams 1986.

Table 2
EXTERNAL EXPOSURE TIMES FOR AQUATIC BIOTA

	Annual Exposure, hrs	
	Sediment	Immersion
Fish	4380	8760
Invertebrates	8760	8760
Algae	-	8760

Table 3
EXTERNAL DOSE FACTORS

	External Dose Factors (total body)	
	Sediment, mrem/hr per pCi/sq m	Water Immersion, mrem/hr per pCi/l
H-3	0.0E+00	0.0E+00
C-14	0.0E+00	0.0E+00
Co-60	1.7E-08	4.6E-06
Sr-89	5.6E-13	4.6E-09
Sr-90	0.0E+00	0.0E+00
Tc-99	0.0E+00	1.3E-10
I-129	4.5E-10	1.7E-08
Cs-137	4.2E-09	1.0E-06
U-234	6.3E-13	8.5E-10
U-235	3.2E-09	2.7E-07
U-238	1.1E-10	2.8E-08
Pu-239	7.9E-13	0.0E+00

Table 4
FRESHWATER BIOACCUMULATION FACTORS

Element	Bioaccumulation Factors		
	Fish	Invert.	Plants
Hydrogen (Tritium)	9.0E-01	9.0E-01	9.0E-01
Carbon	4.6E+03	9.1E+03	4.6E+03
Cobalt	5.0E+01	2.0E+02	2.0E+02
Strontium	3.0E+01	1.0E+02	5.0E+02
Technetium	1.5E+01	5.0E+00	4.0E+01
Iodine	1.5E+01	5.0E+00	4.0E+01
Cesium	3.0E+03	1.0E+02	5.0E+02
Uranium	2.0E+00	6.0E+01	5.0E-01
Plutonium	3.5E+00	1.0E+02	3.5E+02

Table 5
EFFECTIVE ENERGIES FOR INTERNAL DOSE CALCULATIONS

Nuclide	Effective Energy, MeV
H-3	1.0E-02
C-14	5.0E-02
CO-60	2.4E-01
Sr-89	5.6E-01
Sr-90	1.1E+00
Tc-99	8.4E-02
I-129	4.8E-02
Cs-137	2.7E-01
U-234	4.9E+01
U-235	4.6E+01
U-238	4.3E+01
Pu-239	5.5E+01

Table 6
1986 RADIONUCLIDE TRANSPORT IN STREAMS (a)

Nuclide	Curies TB/UTR	BDC	FMC	IGB/PB	SC	PP/LTR	Total
H-3		4.00E+03	1.65E+04	1.11E+04	4.47E+03	4.30E+03	4.03E+04
Sr-89,90 (b)	2.00E-03	5.20E-02	3.80E-01	3.00E-03	2.00E-03	2.00E-03	4.41E-01
I-129			2.20E-02				2.20E-02
Cs-134,137		2.00E-03	1.50E-01	1.00E-03	1.00E-03	1.00E-03	1.55E-01
U-235,238	3.00E-01						3.00E-01
Pu-239	1.00E-03	2.00E-03	1.10E-02	1.00E-03	1.00E-03	1.00E-03	1.70E-02

a. Direct plus indirect releases.
b. Includes unidentified beta-gamma.
c. Includes unidentified alpha.

TB/UTR - Tims Branch and Upper Three Runs
BDC - Beaver Dam Creek
FMC - Four Mile Creek
IGB/PB - Indian Grave Branch and Pen Branch
SC - Steel Creek
PP/LTR - Par Pond and Lower Three Runs

Table 7
CALCULATED DOSE TO AQUATIC BIOTA FROM SRP RELEASE GUIDES (a)

Stream	Location	Flow, cfs	Dose To Biota, mrad/year (b) Fish	Invert	Algae
Upper Three Runs	Rd C	194	3.44	85.60	2.77
Beaver Dam Creek	Below 400-D	85	10.10	13.50	25.20
Four Mile Creek	Rd A-7	21	378.00	442.00	583.00
Pen Branch	Rd B	7	305.00	320.00	359.00
Steel Creek	L-Lake Dam	453	1.95	2.19	2.77
Lower Three Runs	Rd B	32	119.00	112.00	46.80

a. Radioactivity released to streams by seepage and stream bed desorption included in release values.
b. Calculated with LADTAP computer program.

Table 8
MEASURED RADIOACTIVITY IN FISH

	Concentration, pCi/ml or pCi/g										
	1980		1981		1982		1983		1984		1985
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
H-3 In Free Body Water											
Upper Three Runs, Road A	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Four Mile Creek, Road 3	522.0	587.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Steel Creek, Swamp	18.0	32.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Steel Creek, Road A	17.0	22.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Par Pond	18.0	30.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lower Three Runs, Pattersons Mill	9.0	20.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sr-90 In Bone											
Upper Three Runs, Road A	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Four Mile Creek, Road 3	352.0	446.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Steel Creek, Swamp	9.1	21.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Steel Creek, Road A	1.8	6.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Par Pond	11.0	34.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lower Three Runs, Pattersons Mill	0.0	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cs-137 In Total Body											
Upper Three Runs, Road A	ND	ND	ND	ND	ND	ND	0.3	5.0	0.2	1.7	0.0
Four Mile Creek, Road 3	9.4	14.0	16.5	25.0	ND	ND	ND	ND	1.7	4.5	ND
Steel Creek, Swamp	0.7	2.4	1.0	7.4	ND	ND	ND	ND	ND	ND	ND
Steel Creek, Road A	13.0	29.0	17.0	24.0	5.9	13.0	8.9	16.7	8.9	15.0	5.5
Par Pond	3.0	7.0	2.0	4.6	3.1	15.0	1.7	159.0	3.6	103.0	8.9
Lower Three Runs, Pattersons Mill	2.0	4.0	ND	ND	ND	ND	ND	ND	1.5	5.0	0.7

ND - not determined.

Table 9
DOSE FROM MEASURED RADIOACTIVITY IN FISH

Dose to fish, mrad/year

	1980		1981		1982		1983		1984		1985
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Body Water Dose From H-3											
Upper Three Runs, Road A											
Four Mile Creek, Road 3	98	110									
Steel Creek, Swamp	3	6									
Steel Creek, Road A	3	4									
Par Pond	3	6									
Lower Three Runs, Pattersons Mill	2	4									
Bone Dose From Sr-90											
Upper Three Runs, Road A											
Four Mile Creek, Road 3	7496	9498									
Steel Creek, Swamp	194	447									
Steel Creek, Road A	38	128									
Par Pond	234	724									
Lower Three Runs, Pattersons Mill	0	0									
Total Body Dose From Cs-137											
Upper Three Runs, Road A							1	25	1	8	0
Four Mile Creek, Road 3	47	70	82	125					8	22	
Steel Creek, Swamp	3	12	5	37							
Steel Creek, Road A	65	145	85	120	29	65	44	83	44	75	27
Par Pond	15	35	10	23	15	75	8	793	18	514	44
Lower Three Runs, Pattersons Mill	10	20							7	25	3

Enclosure 2

A REVIEW OF THE EFFECTS OF RADIATION ON AQUATIC ORGANISMS

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

and

W. L. Templeton
Earth Sciences Department
Battelle, Pacific Northwest Laboratories**
Richland, Washington

*Operated by Martin Marietta Energy Systems, Inc., under Contract No. DE-AC05-84OR21400 with the U.S. Department of Energy
**Operated by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830 with the U.S. Department of Energy.

A REVIEW OF THE EFFECTS OF RADIATION ON AQUATIC ORGANISMS

B. G. Blaylock

Environmental Sciences Division, Oak Ridge National Laboratory

and W. L. Templeton

Earth Sciences Department, Battelle, Pacific Northwest Laboratories

The problem of assessing the effects of radiation on aquatic organisms has been with us for approximately four decades. During this time an extensive amount of literature has accumulated on the subject, including a number of reviews and symposia (Bacq and Alexander 1961; Ravera 1979; Chipman 1972; Templeton et al. 1971, International Atomic Agency 1976; Blaylock and Trabalka 1978; Egami 1980; National Research Council of Canada 1983). A majority of this literature deals with the effects of large acute doses of external irradiation on aquatic organisms. In comparison, only a small percentage of the studies examine the effects of exposure to chronic irradiation or exposure to radionuclides incorporated within tissue.

Enormous dose (100 kR) may be required to kill poorly integrated organisms, such as bacteria and protozoa, whereas a vertebrate, such as the rabbit, should die within 30 days after an exposure to 800 R. Bacq and Alexander (1961) in their textbook cover the radiological effects literature available to 1960. In general, the authors showed that radiosensitivity increases with increasing complexity in living organisms, i.e., as organisms occupy successively higher phylogenetic positions. This generalization for aquatic biota is illustrated in Table 1 which gives a range of acute lethal doses for various groups of aquatic organisms.

Radiation damage is greatly reduced when chronic or fractionated doses are administered over a long period of time. Fractionating the dose allows repair processes to compensate for the damage (Hevesy et al. 1964; Egami et al. 1967; Rastogi et al. 1969; Cosgrove et al. 1975; Blaylock an dTrabalka 1978; National Research Council of Canada 1983). At very low dose rates, repair processes may keep pace with damage and no detrimental effects will be detected in the organism (Egami and Hama 1975). The effects and the range of dose rates from external exposure to chronic gamma irradiation on various organisms are given in Table 2.

Generally speaking, most aquatic organisms are relatively resistant to ionizing radiation (Templeton et al. 1971). Exceptions to this rule are eggs of some fishes and the early life stages of some invertebrates and fishes, which show damage and lethal effects at approximately the same dose levels that produce effects in mammals. These life stages may show significant damage to some individuals at acute radiation doses in the range of 20-200 rad if irradiated at these critical periods of development (IAEA 1976). With regard to chronic external exposure, some minor effects on physiology or metabolism have been observed at dose rates in the order of 1 rad/day.

Studies dealing with developing fish embryos exposed to chronic external irradiation are addressed in Table 2. Another common type of experiment involved exposing developing fish embryos to a medium containing a radionuclide. In most cases a dose-effect relationship could not be established because the concentration of the radionuclide within tissues was not known. As a result, the dose rate was difficult, if not impossible to determine; therefore, more often than not, the effects on developing embryos were related to radionuclide concentrations in the medium rather than dose rate.

Polikarpov (1966) reported extreme sensitivity of developing fish embryos to trace quantities of radionuclides that delivered dose rates to embryos that were only fractions of background (Woodhead 1970). Brown and Templeton (1964) attempted to confirm Polikarpov's results by exposing plaice eggs to chronic gamma irradiation at dose rates up to 1 rad/h. They found no significant difference in the percentage of control and irradiated eggs that hatched or in the number of abnormal larvae produced. Other investigators also tried to repeat Polikarpov's results without success (for review see Blaylock and Trabalka 1978). This controversy influenced several investigators to perform rigorous dosimetric treatments for radiobiological studies of fish embryos (Adams 1968; Woodhead 1970). Detailed reviews of these studies can be found in IAEA (1976) and Blaylock and Trabalka (1978).

In comparison with mice and *Drosophila*, very little information is known about the cytological and genetic effects of radiation on aquatic organisms. Schroder (1973) surveyed the literature on the mutation rate in fish, and Blaylock and Trabalka (1978) reviewed cytological effects of irradiation as well as radiation-induced mutation rates in aquatic organisms. A comparison of the mutation rates for fish with those of *Drosophila* and mice indicated that the estimated mutation rate for fish is between those for *Drosophila* and mice (Blaylock and Trabalka 1978). In regard to chromosome breakage, the sensitivity of aquatic organisms is comparable to, but may be less than, the well-studied *Drosophila* and mammalian systems (Blaylock and Trabalka 1978).

It is generally accepted that radiation (and other mutagens) exert their long-term effects on the fitness of populations through the increased induction of mutations. Because of the high reproductive rate of most aquatic organisms and the relative low importance of one or even thousands of individual organisms to the long-term structure and fate of aquatic populations, it generally assumed that significant deleterious effects would not be detected on aquatic populations exposed to a dose rate of 1 rad per day or less (IAEA 1976; Blaylock and Trabalka 1978; National Research Council of Canada 1983).

Little information is available on the chemical versus radiological toxicity of radioactive elements to aquatic biota. In one of the few studies available, Till et al. (1976) and Till and Frank (1977) use solutions containing high specific activity ^{238}Pu or ^{232}U or low specific activity ^{244}Pu, ^{235}U, or ^{238}U to investigate the chemical toxicity of plutonium and uranium on the developing embryos of fathead minnows and carp. Their results showed that the potential chemical toxicity of plutonium may be more important than the radiological toxicity; however, a chemical toxicity from low specific activity uranium was not found.

Environmental factors such as salinity and temperature can influence the effects of radiation on aquatic organism (see review in National Research Council of Canada 1983). It appears that temperature is the most important environmental factor that influences the expression of radiation damage in poikilothermic aquatic organisms (Engle 1979). In general, lower temperatures lengthen the period of time between radiation exposure and the expression of radiation effects, while high temperatures reduce this time period.

One of the problems encountered in evaluating the effects of radiation on aquatic organisms or populations of organisms inhabiting an environment contaminated with radioactivity is the estimation of absorbed dose. Organisms in such environments receive a dose from internal emitters as a result of radionuclides assimilated from food and absorbed from water. They receive an external exposure from immersion in water that contains radioactivity; in addition, some types of biota will receive an external exposure from radionuclides accumulated in sediment. Dose equations and geometric factors for estimating radiation absorbed dose to aquatic organisms have been provided by Woodhead (1974) and IAEA (1976). In these calculations, simplified idealized models were used to represent various groups of aquatic organisms to improve the accuracy of dose estimates. Computer codes that require as input only the concentration of a radionuclide in water or sediment have been developed at the Oak Ridge National Laboratory to estimate external and internal radiation doses to aquatic organisms. EXREM III estimates the dose rate and the total dose to aquatic organisms from submersion in contaminated water (Trubey and Kay 1973). BIORAD (Killough and McKay 1976) is a computer code developed to estimate the internal dose to aquatic organisms. With an input of a concentration of a radionuclide, these computer codes can estimate internal and external radiation doses to aquatic plants, invertebrates, fish, and terrestrial animals consuming aquatic plants.

These computer codes (EXREM III and BIORAD) were used with the available literature to predict the effects of irradiation on aquatic biota resulting from radioactive releases from model facilities of the nuclear fuel cycle to representative, hypothetical, aquatic environments (Blaylock and Witherspoon 1975). They concluded that no significant deleterious effects would be predicted for a population of aquatic organisms for the dose rates estimated for routine releases of radionuclides from conversion, enrichment, fabrication, reactors and reprocessing facilities. At the higher dose rates estimated for milling and mining operations, Blaylock and Witherspoon (1975) predicted that it would still be difficult to detect radiation effects on aquatic populations.

In summary, literature on radiation effects and methods for estimating the dose to aquatic biota are available for predicting the effects of radioactive effluents from nuclear facilities on aquatic biota. It is generally accepted that exposure of aquatic biota at 1 rad per day or less will not produce detectable deleterious effects on populations of these organisms (National Academy of Sciences 1972). However, at levels approaching 1 rad per day, additional supporting data would be desirable to definitively confirm the absence of detrimental effects on aquatic populations.

REFERENCES

Adams, N. 1968. Dose-rate distribution from spherical and spherical-shell radiation sources with special reference to fish eggs in radioactive media. United Kingdom Atomic Energy Authority Harewell, Didcot, Berkshire, KAHSV (RP)87, Her Majesty's Stationery Office, London. 14 pp.

Bacq, Z. M. and P. Alexander. 1961. Fundamentals of radiobiology. 2nd ed. Pergamon Press, Oxford. Chap. 12, pp. 299-310.

Blaylock, B. G. and J. P. Witherspoon. 1975. "Dose estimation and prediction of radiation effects on aquatic biota resulting from radioactive releases from the nuclear fuel cycle," *In* Symposium on Impacts of Nuclear Release into the Aquatic Environment, IAEA, Vienna. p. 377.

Blaylock, B. G. and J. R. Trabalka. 1978. Evaluating the effects of ionizing radiation on aquatic organisms. *In* Advances in Radiation Biology 7 (Lett, J. T. and H. Adler, Eds.) Academic Press, New York. pp. 103-152.

Brown, V. M. and W. L. Templeton. 1964. Resistance of fish embryos to chronic irradiation. Nature (London) 203:1257-1259.

Chipman, W. A. 1972. "Ionizing radiation," *In* Marine Ecology, A Comprehensive Integrated Treatise on Life in Oceans and Coastal Waters (Kinne, O., Ed.), Wiley-Interscience, New York. 1478 pp.

Cooley, J. L. and F. L. Miller, Jr. 1971. Effects of chronic irradiation on laboratory populations of the aquatic snail *Physa heterostropha*. Radiat. Res. 47:716-724.

Cosgrove, G. E., B. G. Blaylock, G. V. Ulrickson and P. C. Cohan. 1975. *In* Pathology of Fishes (Ribelin, W. E., and G. Migaki Eds.), The University of Wisconsin Press, Madison, Wisconsin. pp. 453-476.

Donaldson, L. B. and K. Bonham. 1964. Effects of low-level chronic irradiation of Chinook and Coho salmon eggs and alevins. Trans. Am. Fish Soc. 93:333-341.

Donaldson, L. B. and K. Bonham. 1970. Effects of chronic exposure of Chinook salmon eggs and alevins to gamma irradiation. Trans. Am. Fish. Soc. 99:112-119.

Egami, N. (Editor). 1980. Radiation Effects on Aquatic Organisms. University Park Press, Baltimore. 292 pp.

Egami, N. and A. Hama. 1975. Dose-rate effects on the hatchability of irradiated embryos of the fish Oryzias latipes. Int. J. Radiat. Biol. 28(3):273-278.

Egami, N., Y. Hyodo-Taguchi and H. Etoh. 1967. Recovery from radiation effects in organized cell populations in fish at different temperatures. Proc. Int. Conf. Radiat. Biol. Cancer, Kyoto (1966). Radiation Society of Japan. pp. 117-123.

Engel, D. W. 1967. Effect of single and continuous exposures of gamma radiation on the survival and growth of the blue crab, *Callinectes sapidus*. Radiat. Res. 32:685-691.

Engel, D. W. 1979. Experimental approaches to demonstrate the interaction of radiation with other environmental stresses. *In* Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems. International Atomic Energy Agency. IAEA Tech. Rept. Ser. 190. pp. 301-316.

Hevesy, G. V., D. Lockner and K. Sletten. 1964. On the radiation sensitivity of extramedullary hematopoiesis. Med. Welt 10:455-460.

IAEA. 1976. Effects of ionizing radiation on aquatic organisms and ecosystems. International Atomic Energy Agency, Vienna. IAEA Tech. Rep. Ser. No. 172. 131 pp.

Kaufman, G. A. and R. J. Beyers. 1973. Effects of chronic irradiation on the fish, *Oryzias latipes*. *In* Radionuclides in Ecosystems. Proc. 3rd Natl. Symp. Radioecology (Nelson, D. J. Ed) U.S. AEC Tech. Inf. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tennessee. CONF-710501. pp. 1119-1124.

Killough, G. G. and L. R. McKay. 1976. A methodology for calculating radiation doses from radioactivity released to the environment. Oak Ridge National Laboratory, Oak Ridge, Tennessee. ORNL-TM-4322.

National Academy of Sciences. 1972. The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. National Academy of Science, Washington, D.C. 217 pp.

National Research Council of Canada. 1983. Radioactivity in the Canadian Environment. Publication No. NRCC 19250 of the Environmental Secretariat, Ottawa, Canada. 292 pp.

Polikarpov, G. G. 1966. Radioecology of Aquatic Organisms. Reinhold, New York. 314 pp.

Rastogi, R. K., Y. Hyodo-Taguchi, and N. Egami. 1969. Effects of fractionated whole-body X-irradiation on cell proliferation in the intesting of the goldfish, Carassium auratus. Annot. Zool. Jpn. 42:193-202.

Raverà, O. (Editor). 1979. Biological effects of ionizing radiation in aquatic environment. *In* Biological Aspects of Freshwater Pollution. Pergamon Press, Oxford. pp. 179-197.

Schroder, J. H. (Editor). 1973. Genetics and Mutagenesis of Fish. Springer-Verlag, Berlin and New York. 356 pp.

Templeton, W. L., R. E. Nakatani and E. E. Held. 1971. Radiation effects. *In* Radioactivity in the Marine Environment. National Academy of Sciences, Washington, D.C. pp. 223-240.

Till, J. E. and M. L. Frank. 1977. Bioaccumulation, distribution and dose of Am-241, Cm-244 and Pu-239 in developing fish embryos. Proc. 4th Int. Congr. Int. Radiat. Prot. Assoc., Gauthier-Villars, Montreuil, France. pp. 645-648.

Till, J. E. 1976. The toxicity of uranium and plutonium to the developing embryos of fish (thesis). Oak Ridge National Laboratory. Oak Ridge, Tennessee. ORNL-5160. 193 pp.

Trubey, D. K. and S. V. Kaye. 1973. The EXREM III computer code for estimating external radiation doses to populations from environmental releases. Oak Ridge National Laboratory, Oak Ridge, Tennessee. ORNL-TM-4322.

Woodhead, D. S. 1970. The assessment of the radiation dose to developing fish embryos due to the accumulation of radioactivity in the egg. Radiat. Res. 43:582-597.

Woodhead, D. S. 1974. The estimation of radiation dose rates to fish in contaminated environments, and the assessment of the possible consequences. *In* Population Dose Evaluation and Standards for Man and his Environment. International Atomic Energy Agency, Vienna. pp. 555-576.

Table 1. Ranges of acute lethal radiation doses for adults of various groups of aquatic organisms (after IAEA 1976)

Organism	Dose Range (Kilorads)	
Bacteria	4.5-735	(LD90)
Blue-green algae	<400 - >1200	(LD90)
Other algae	3-120	(LD50)
Protozoa	100-600	(LD50)
Mollusca	20-109	(LD50/30)
Crustaceans	1.5-56.6	(LD50/30)
Fish	1.1-56	(LD50/30)