PUC

Série: Monografias em Ciência da Computação

Nº 7/77

(antiga/formerly: Monographs in Computer Science and Computer Applications)

COMPUTER KINETIC MODELLING OF RADIONUCLIDE ACCUMULATION IN MARINE ORGANISMS

by

H.M. Quintella, D. Santimateo, A.S. Paschoa

Departamento de Informática

Pontifícia Universidade Católica do Rio de Janeiro

Rua Marquês de São Vicente 225 — ZC 19

Rio de Janeiro — Brasil

Série: Monografias em Ciência da Computação
Nº 7/77

(antiga/formerly: Monographs in Computer Science and Computer Applications)

COMPUTER KINETIC MODELLING OF RADIONUCLIDE ACCUMULATION IN MARINE ORGANISMS*

by

H.M. Quintella, D. Santimateo[+], A.S. Paschoa[++]

Editor: Michael F. Challis julho 1977

* Work partially sponsored by: FINEP, CNEN, UNIPAN-BID, IAEA IBM do Brasil and IBM Japan

Accepted in the IFAC Symposium on Environmental Systems Planning Design and Control, Kyoto, Japan, Aug. 1977, to be published by Pergamon Press.

+ Present address: Universidad de Panama, Faculdad de Ciencias, Departamento de Matematicas, Panama, Republica de Panama.

++ Departamento de Física, PUC/RJ

RESUMO:

CSMP é usado para simular o primeiro estágio da cinética de um radionuclídeo numa cadeia alimentar. Como ilustração foi usado o modelo exponencial de acumulação de água para algas baseado em dados encontrados na literatura. O uso da modelagem computacional como um instrumento para estudos ambientais é discutido em termos das vantagens econômicas e futuras aplicações.

PALAVRAS CHAVE:

acumulação de radionuclídeos, biota aquática, metodologia de modelagem, modelagem computacional cinética, organização de grupos de pesquisa.

ABSTRACT:

Continuous System Modelling Program (CSMP) is used to simulate the first step of the Kinetic of a radionuclide in a food chain by using the exponential model of accumulation from water-to-algae based on data found in the literature. The use of computer moddeling as a tool for environmental studies is discussed as far as economical advantages and future applications are concerned.

KEY WORDS:

Aquatic biota, computer kinetic modelling, continuous simulation, modelling methodology, radionuclide accumulation, research team organization.

CONTENTS

1 - INTRODUCTION

There is an increasing motivation to study the environmental impact of nuclear power programs. Environmental models which describe the pathways of radionuclides introduced in the biosphere, from source to biological entities, start being widely used. Compartment models with rates of transfer either constants or as functions of time are usually employed.

The first order kinetics of transference of radionuclide in a food chain may be represented by differential equations analogous to those describing the radioactive decay series. It is well known that the initial part of a radioactive decay series is represented schematically as follows: - see, for example, Evans (1) -

$$R_1 \xrightarrow{\lambda 1} R_2 \xrightarrow{\lambda 2} R_3,$$

where R_1, R_2, and R_3 are the first radionuclides of the series; and λ_1, and λ_2 are the decay constants of R_1 and R_2, respectively.

Accordingly, the first steps of the kinetics of radionuclide in a food chain have been simulated by Eberhard (2), assuming transfer coefficients, from source to plant and from plant to one or two-compartment animals, independent of time. Reichle et al. (3) mention several applications of kinetic models for concentration of radionuclides in food chains.

The present work is a simple application of a modified version of the first step of Eberhard's model, represented as follows:

$$\begin{array}{ccccc} Y_S & \xrightarrow{C} & Y_P & \xrightarrow{C'} & Y_A, \\ \downarrow & & \downarrow & & \\ \beta & & \mu & & \end{array}$$

where Y_S, Y_P, and Y_A are concentrations of a radionuclide, respectively, in the source (i.e., activity concentration in water), plant (for example, phytoplankton), and one compartment animal; β is the loss rate of the radionuclide in the source; $C = Y_P/Y_S$ is the transfer coefficient of the radionuclide from the source to the plant (i.e., the concentration-or de-concentration-factor from water-to-algae as a function of time); μ is the loss rate of the radionuclide in the plant (i.e., the biological decay constant

of the radionuclide from the plant to a one compartment animal (i.e., the concentration or de concentration factor from algae-to-one compartment animal).

The usual exponential model which describes the concentration factors, C(t) of radionuclides in marine organisms may be represented as.

$$C(t) = C(\infty)(1 - e^{-\lambda t}).$$

where: $C(\infty)$ is the concentration factor after the accumulation process has reached a steady state; λ is the characteristic coefficient of the release process, and t is the time after accumulation started.

The use of this model implies the knowledge of the characteristic coefficient, λ, to fit the experimental data, C(t). The usual procedure to determine λ is to undertake experiments to measure the rate of release of the radionuclide in question. However, this type of procedure is based upon the assumption that the biological mechanism of release is of the same nature as that of accumulation. Besides, when the accumulation rates are suspected to be different for short and long terms, it is necessary to establish two different values of λ if the exponential model is to be used for short as well as long term experimental results.

Polikarpov et al. (4), based on a literature review of the abilities of various marine organisms to accumulate radionuclides in different regions of the world oceans, pointed out that the kinetics of accumulation of radionuclides by marine organisms is not necessarily of an exponential character. According to Polikarpov, the phenomenon of accumulation of radionuclides by aquatic organisms may be better described by the generalized forms of logarithmic and power functions among others. As a matter of fact, short term (less than 200 hours) experiments performed with zooplankton accumulating ^{226}Ra under laboratory conditions (Ref. 5) have shown that both, logarithmic and power functions, can fit limited data taken during the accumulation period.

In any case, simulation can be a helpful tool to determine the best function to describe the accumulation process of a radionuclide by a particular species of marine organisms. Once a

function which describes the process is established, extremely valuable information may be obtained by inserting known parameters.

2 - THE USE OF COMPUTER MODELLING AS AN INSTRUMENT OF RESEARCH

The use of computer modelling is highly recommended in at least three circumstances:

a) When experiments with the real systems can neither be done directly nor be reproduced under laboratory conditions;

b) when it is economically less expensive to manipulate a model rather than carry out an experiment with the real system; and

c) when one wants to test different hypotheses about a certain experiment.

In the specific case of radionuclide accumulation in marine organisms the last two circumstances are important factors that recommend the use of modelling for research in the field. Nevertheless the first circumstance also plays a minor role since it is not always possible to carry out experiments with such systems and when it is possible this is in general an expensive exercise.

In planning one such research project in a traditional manner one would have a hierarchy of activities such as the one shown in Fig.1 (Next page).

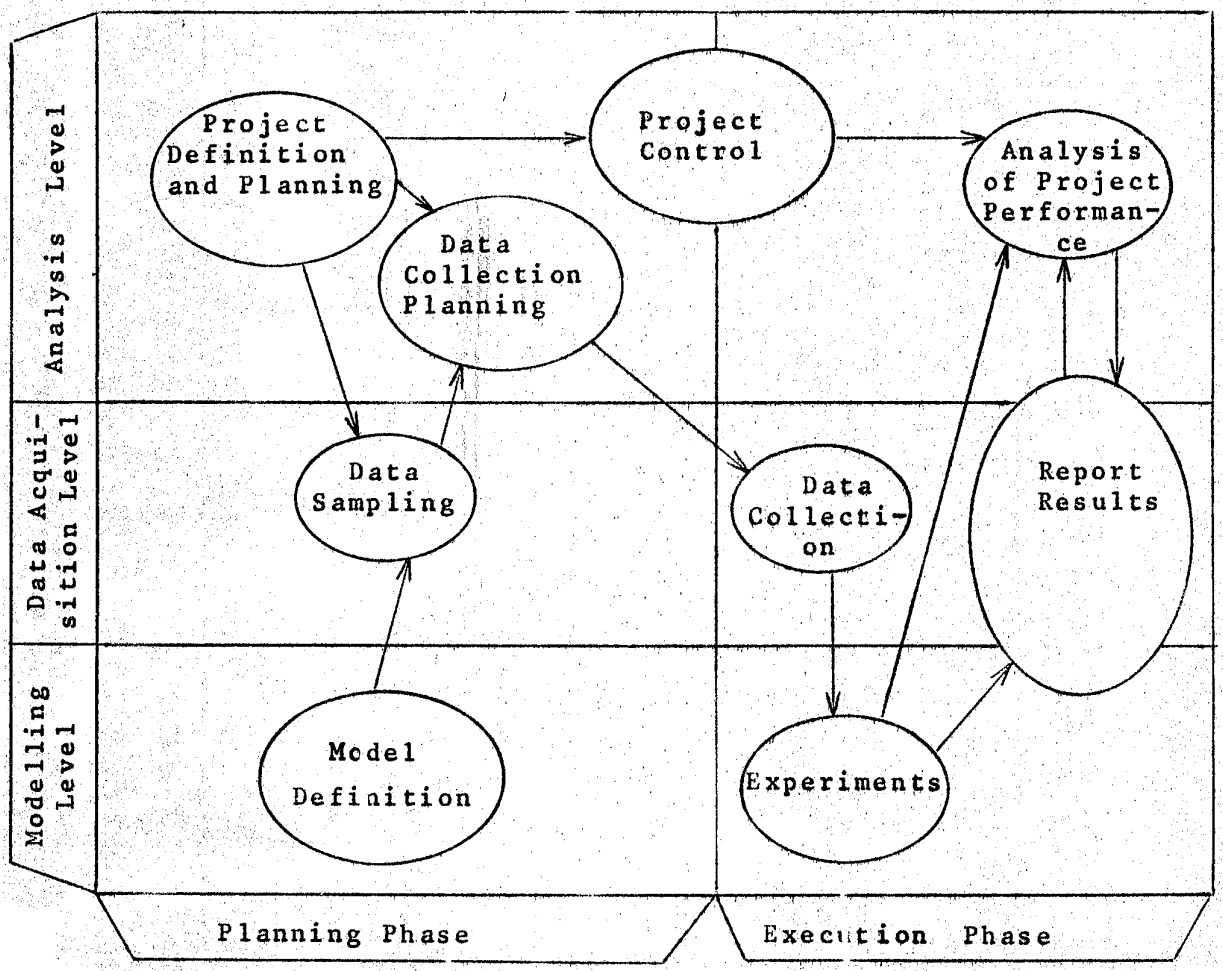

Fig. 1. Levels of hierarchy of activities for a research project.

In Fig. 1 the nodes represent the activities and the edges represent precedence relations. Clearly the "data sampling" activity is a necessity in projects where "data collection" is important. However, in order to reduce costs it is possible (in some cases) to replace real "data sampling" by a simulation exercise and in this manner guide the "data collection" activity and partially subsidize it by saving through simulation.

Amongst the many tools that exist nowadays to aid computer modelling as a research instrument, one of the most important in the field of continuous digital simulation is IBM's CSMP (Continuous Systems Modelling Program) (Refs. 6 to 9).

CSMP is a digital simulator devised to model continuous system by combining analogic functional blocks with logic and algebraic facilities of FORTRAN IV. In this paper a CSMP package for the IBM 370/165 was used as a tool to test the exponential model of accumulation of radionuclides in marine organisms based on data published in the literature (Ref. 10).

A number of integration methods are available in CSMP. The method chosen for use in the present work was the fourth order Runge Kutta with variable integration interval (See appendix A).

The simulation exercise reported in this work is based upon a model described by the following differential equation:

$$\frac{dY_P}{dt} + \mu Y_P = \left(\frac{C}{\tau}\right) Y_S$$

where Y_S, Y_P, and μ have the same meaning as in the preceding section; $\tau = 1/\lambda$ is the biological half-life of the radionuclide (^{60}Co) for a particular species of marine organisms; and C is given by the usual exponential model mentioned earlier.

Here it is important to observe that the loss of rate, β, defined earlier, can be considered neglibible for radionuclides with long half lives (e.g., ^{60}Co, 5.26 years) when compared to the accumulation time to reach a steady state.

3 - RESULTS AND DISCUSSION

Data taken from Nakahara et al. (10) on the concentration of radioactive cobalt by three species of seaweed (brown algae - Sargassum Thunbergii and Laminaria japonica; and red algae Ahnfeltia paradoxa) are summarized in TABLE 1.

TABLE 1 Data on $C(\infty)$, τ and μ for Co-60 in seaweed taken from Nakahara et al. (10)

	S. Thunbergii	Laminaria	Ahnfeltia
$C(\infty)$	2.6×10^{3}	1.4×10^{2}	3.0×10^{2}
τ(day)	7.5	14	4.3
μ(day^{-1})	9.3×10^{-2}	2.8×10^{-2}	3.4×10^{-2}

TIPO DE ALGA "LAMINARIA" PAGE 3

MINIMUM YP VERSUS TIME MAXIMUM
0.0 5.0042E 01

TIME	YP
0.0	0.0
2.0000E 00	1.3720E-01
4.0000E 00	7.0205E-01
6.0000E 00	1.4317E 00
8.0000E 00	2.4729E 00
1.0000E 01	3.6304E 00
1.2000E 01	4.9162E 00
1.4000E 01	6.2974E 00
1.6000E 01	7.7474E 00
1.8000E 01	9.2431E 00
2.0000E 01	1.0765E 01
2.2000E 01	1.2259E 01
2.4000E 01	1.3731E 01
2.6000E 01	1.5349E 01
2.8000E 01	1.6847E 01
3.0000E 01	1.8316E 01
3.2000E 01	1.9751E 01
3.4000E 01	2.1149E 01
3.6000E 01	2.2506E 01
3.8000E 01	2.3813E 01
4.0000E 01	2.5085E 01
4.2000E 01	2.6305E 01
4.4000E 01	2.7491E 01
4.6000E 01	2.8603E 01
4.8000E 01	2.9690E 01
5.0000E 01	3.0726E 01
5.2000E 01	3.1716E 01
5.4000E 01	3.2668E 01
5.6000E 01	3.3565E 01
5.8000E 01	3.4428E 01
6.0000E 01	3.5249E 01
6.2000E 01	3.6032E 01
6.4000E 01	3.6775E 01
6.6000E 01	3.7485E 01
6.8000E 01	3.8159E 01
7.0000E 01	3.8799E 01
7.2000E 01	3.9406E 01
7.4000E 01	3.9984E 01
7.6000E 01	4.0532E 01
7.8000E 01	4.1054E 01
8.0000E 01	4.1549E 01
8.2000E 01	4.2019E 01
8.4000E 01	4.2463E 01
8.6000E 01	4.2883E 01
8.8000E 01	4.3279E 01
9.0000E 01	4.3653E 01
9.2000E 01	4.4005E 01
9.4000E 01	4.4335E 01
9.6000E 01	4.4646E 01
9.8000E 01	4.4938E 01
1.0000E 02	4.5212E 01
1.0200E 02	4.5469E 01
1.0400E 02	4.5710E 01
1.0600E 02	4.5936E 01
1.0800E 02	4.6147E 01
1.1000E 02	4.6345E 01
1.1200E 02	4.6530E 01
1.1400E 02	4.6703E 01
1.1600E 02	4.6865E 01
1.1800E 02	4.7017E 01
1.2000E 02	4.7160E 01
1.2200E 02	4.7294E 01
1.2400E 02	4.7419E 01
1.2600E 02	4.7536E 01
1.2800E 02	4.7646E 01
1.3000E 02	4.7749E 01
1.3200E 02	4.7846E 01
1.3400E 02	4.7937E 01
1.3600E 02	4.8022E 01
1.3800E 02	4.8102E 01
1.4000E 02	4.8177E 01
1.4200E 02	4.8247E 01
1.4400E 02	4.8313E 01
1.4600E 02	4.8375E 01
1.4800E 02	4.8433E 01
1.5000E 02	4.8487E 01
1.5200E 02	4.8538E 01
1.5400E 02	4.8586E 01
1.5600E 02	4.8631E 01
1.5800E 02	4.8673E 01
1.6000E 02	4.8713E 01
1.6200E 02	4.8750E 01
1.6400E 02	4.8785E 01
1.6600E 02	4.8818E 01
1.6800E 02	4.8849E 01
1.7000E 02	4.8878E 01
1.7200E 02	4.8905E 01
1.7400E 02	4.8931E 01
1.7600E 02	4.8955E 01
1.7800E 02	4.8977E 01
1.8000E 02	4.8998E 01
1.8200E 02	4.9018E 01
1.8400E 02	4.9037E 01
1.8600E 02	4.9055E 01
1.8800E 02	4.9071E 01
1.9000E 02	4.9087E 01
1.9200E 02	4.9102E 01
1.9400E 02	4.9116E 01
1.9600E 02	5.0005E 01
1.9800E 02	5.0024E 01
2.0000E 02	5.0042E 01

(a)

Fig.2. Results of simulation for Y_P (cpm/g) for a time-range from zero to 200 days: a) Laminaria

TIPO DE ALGA **AHNFELTIA**

MINIMUM 0.0 YP VERSUS TIME MAXIMUM 2.9114E 02

TIME	YP
0.0	0.0
2.0000E 00	3.8243E 00
4.0000E 00	1.3006E 01
6.0000E 00	2.5113E 01
8.0000E 00	3.8547E 01
1.0000E 01	5.2692E 01
1.2000E 01	6.6760E 01
1.4000E 01	8.0347E 01
1.6000E 01	9.3436E 01
1.8000E 01	1.0591E 02
2.0000E 01	1.1773E 02
2.2000E 01	1.2885E 02
2.4000E 01	1.3930E 02
2.6000E 01	1.4911E 02
2.8000E 01	1.5831E 02
3.0000E 01	1.6692E 02
3.2000E 01	1.7499E 02
3.4000E 01	1.8253E 02
3.6000E 01	1.8959E 02
3.8000E 01	1.9620E 02
4.0000E 01	2.0238E 02
4.2000E 01	2.0815E 02
4.4000E 01	2.1355E 02
4.6000E 01	2.1861E 02
4.8000E 01	2.2334E 02
5.0000E 01	2.2776E 02
5.2000E 01	2.3190E 02
5.4000E 01	2.3578E 02
5.6000E 01	2.3940E 02
5.8000E 01	2.4278E 02
6.0000E 01	2.4593E 02
6.2000E 01	2.4888E 02
6.4000E 01	2.5165E 02
6.6000E 01	2.5423E 02
6.8000E 01	2.5665E 02
7.0000E 01	2.5892E 02
7.2000E 01	2.6105E 02
7.4000E 01	2.6304E 02
7.6000E 01	2.6491E 02
7.8000E 01	2.6665E 02
8.0000E 01	2.6828E 02
8.2000E 01	2.6979E 02
8.4000E 01	2.7119E 02
8.6000E 01	2.7249E 02
8.8000E 01	2.7370E 02
9.0000E 01	2.7482E 02
9.2000E 01	2.7586E 02
9.4000E 01	2.7682E 02
9.6000E 01	2.7770E 02
9.8000E 01	2.7851E 02
1.0000E 02	2.7926E 02
1.0200E 02	2.7995E 02
1.0400E 02	2.8059E 02
1.0600E 02	2.8117E 02
1.0800E 02	2.8171E 02
1.1000E 02	2.8221E 02
1.1200E 02	2.8267E 02
1.1400E 02	2.8309E 02
1.1600E 02	2.8348E 02
1.1800E 02	2.8384E 02
1.2000E 02	2.8417E 02
1.2200E 02	2.8447E 02
1.2400E 02	2.8475E 02
1.2600E 02	2.8501E 02
1.2800E 02	2.8525E 02
1.3000E 02	2.8547E 02
1.3200E 02	2.8567E 02
1.3400E 02	2.8586E 02
1.3600E 02	2.8603E 02
1.3800E 02	2.8619E 02
1.4000E 02	2.8634E 02
1.4200E 02	2.8648E 02
1.4400E 02	2.8661E 02
1.4600E 02	2.8673E 02
1.4800E 02	2.8684E 02
1.5000E 02	2.8694E 02
1.5200E 02	2.8704E 02
1.5400E 02	2.8713E 02
1.5600E 02	2.8722E 02
1.5800E 02	2.8730E 02
1.6000E 02	2.8738E 02
1.6200E 02	2.8745E 02
1.6400E 02	2.8752E 02
1.6600E 02	2.8759E 02
1.6800E 02	2.8765E 02
1.7000E 02	2.8771E 02
1.7200E 02	2.8777E 02
1.7400E 02	2.8782E 02
1.7600E 02	2.8787E 02
1.7800E 02	2.8792E 02
1.8000E 02	2.8797E 02
1.8200E 02	2.8801E 02
1.8400E 02	2.8805E 02
1.8600E 02	2.8809E 02
1.8800E 02	2.8813E 02
1.9000E 02	2.8817E 02
1.9200E 02	2.8821E 02
1.9400E 02	2.8824E 02
1.9600E 02	2.8828E 02
1.9800E 02	2.8831E 02
2.0000E 02	2.8834E 02

(b)

Fig.3. Results of simulation for Y_p (cpm/g) for a time-range from zero to 200 days: b) Ahnfeltia

TIPO DE ALGA **THUNBERGII**

PAGE 1

MINIMUM 0.0 YP VERSUS TIME MAXIMUM 5.2186E 02

TIME	YP
.0	0.0
2.0000E 00	1.1147E 01
4.0000E 00	3.8525E 01
6.0000E 00	7.5133E 01
8.0000E 00	1.1617E 02
1.0000E 01	1.5831E 02
1.2000E 01	1.9965E 02
1.4000E 01	2.3872E 02
1.6000E 01	2.7440E 02
1.8000E 01	3.0755E 02
2.0000E 01	3.3991E 02
2.2000E 01	3.7029E 02
2.4000E 01	3.9857E 02
2.6000E 01	4.0572E 02
2.8000E 01	4.2301E 02
3.0000E 01	4.3754E 02
3.2000E 01	4.5075E 02
3.4000E 01	4.6175E 02
3.6000E 01	4.7112E 02
3.8000E 01	4.7907E 02
4.0000E 01	4.8584E 02
4.2000E 01	4.9161E 02
4.4000E 01	4.9645E 02
4.6000E 01	5.0056E 02
4.8000E 01	5.0399E 02
5.0000E 01	5.0693E 02
5.2000E 01	5.0934E 02
5.4000E 01	5.1139E 02
5.6000E 01	5.1311E 02
5.8000E 01	5.1455E 02
6.0000E 01	5.1576E 02
6.2000E 01	5.1677E 02
6.4000E 01	5.1761E 02
6.6000E 01	5.1832E 02
6.8000E 01	5.1891E 02
7.0000E 01	5.1940E 02
7.2000E 01	5.1981E 02
7.4000E 01	5.2015E 02
7.6000E 01	5.2044E 02
7.8000E 01	5.2068E 02
8.0000E 01	5.2088E 02
8.2000E 01	5.2104E 02
8.4000E 01	5.2118E 02
8.6000E 01	5.2129E 02
8.8000E 01	5.2139E 02
9.0000E 01	5.2147E 02
9.2000E 01	5.2153E 02
9.4000E 01	5.2159E 02
9.6000E 01	5.2164E 02
9.8000E 01	5.2167E 02
1.0000E 02	5.2171E 02
1.0200E 02	5.2173E 02
1.0400E 02	5.2175E 02
1.0600E 02	5.2177E 02
1.0800E 02	5.2179E 02
1.1000E 02	5.2180E 02
1.1200E 02	5.2181E 02
1.1400E 02	5.2182E 02
1.1600E 02	5.2183E 02
1.1800E 02	5.2183E 02
1.2000E 02	5.2184E 02
1.2200E 02	5.2184E 02
1.2400E 02	5.2184E 02
1.2600E 02	5.2185E 02
1.2800E 02	5.2185E 02
1.3000E 02	5.2185E 02
1.3200E 02	5.2185E 02
1.3400E 02	5.2185E 02
1.3600E 02	5.2186E 02
1.3800E 02	5.2186E 02
1.4000E 02	5.2186E 02
1.4200E 02	5.2186E 02
1.4400E 02	5.2186E 02
1.4600E 02	5.2186E 02
1.4800E 02	5.2186E 02
1.5000E 02	5.2186E 02
1.5200E 02	5.2186E 02
1.5400E 02	5.2186E 02
1.5600E 02	5.2186E 02
1.5800E 02	5.2186E 02
1.6000E 02	5.2186E 02
1.6200E 02	5.2186E 02
1.6400E 02	5.2186E 02
1.6600E 02	5.2186E 02
1.6800E 02	5.2186E 02
1.7000E 02	5.2186E 02
1.7200E 02	5.2186E 02
1.7400E 02	5.2186E 02
1.7600E 02	5.2186E 02
1.7800E 02	5.2186E 02
1.8000E 02	5.2186E 02
1.8200E 02	5.2186E 02
1.8400E 02	5.2186E 02
1.8600E 02	5.2186E 02
1.8800E 02	5.2186E 02
1.9000E 02	5.2186E 02
1.9200E 02	5.2186E 02
1.9400E 02	5.2186E 02
1.9600E 02	5.2186E 02
1.9800E 02	5.2186E 02
2.0000E 02	5.2186E 02

Fig.4. Results of simulation for Y_p (cpm/g) for a time-range from zero to 200 days : c) S.Thunbergii

The results of simulation for Y_p (in cpm/g), for a time-range between zero and 200 days, based upon the data presented in TABLE 1 and the differential equation writen in the preceding section are presented in Fig. 2.

From the results shown in Fig. 2 one can observe that according to the exponential model used for the simulation 95% of the steady state concentration of ^{60}Co in the algae Laminaria, Ahnfeltia, and S. Thunbergii are reached respectively at 122, 93, and 43 days after accumulation started. Such results are entirely consistent with the short term (maximum twenty days) accumulation experiments reported by Nakahara et al. (10).

Thus, laboratory experiments to study the concentrations of ^{60}Co in those species of algae should be extended to time-ranges neither much longer, nor much shorter than the times found to be necessary, by using the exponential model, to accumulate 95% of the steady state concentration of ^{60}Co in the organisms. On the other hand, an optimization of those findings can be achieved by trying models and by using more experimental data.

4 - CONCLUSIONS

Saving Through Simulation

In performing data acquisition for a study of radionuclide accumulation in marine organisms one needs at least the following equipment: sporting or fishing boat (fuel, maintenance), sampling material, storage facilities (tanks, freezers, etc.), and detection systems (γ and α spectrometers).

In most case the lease/hire cost of equipment is approximately the same in "data sampling" and "data collection" activities. The personnel cost may be reduced in "data sampling" activities but not substantially. In TABLE 2 we show minimum estimated costs for "data collection" and "data sampling" in US$ per week according to Quintella (11).

TABLE 2 Estimated costs in US$/week prices of May 1976 in Greater Rio area

with rate of exchange US$ 1.00 Cr$ 10,00

		"Data collection"	Simulation
Personnel	Number	10	3
	Cost (US$)	1200.00	300.00
Equipment		800.00	(10x)10.00

Such results allow as a conclusion that in a research institution that already has access to a computer system it is possible to make substantial savings by the use of computer simulation in projects in which "data collection" is an important phase.

Structuring a Research Team that Uses Modelling as an Instrument

The substance of computer simulation is the indirect study of a process P by investigating a computation process P' similar to P and such that P' models P. One of the many problems here is how to program the process P' and verify its similarity to P. Winkowsky (12) and Klir (13) propose theoretical solutions to such problems. In practical terms one important result of their theory is that the environmental scientists must have a reliable and easily accessible experimental data bank (EDB) in order to validate computer models and check their correctness.

Consequently, the use of computer modelling to supplement or

replace "data sampling" requires:

a) easy access to a computer system with appropriate reliable software; and

b) the existence of a scientific team composed at least of an EDB administrator and a systems modelist to aid the environmental scientist (the systems analist) in his work.

Future Applications

Much research is still necessary until a comprehensive computer kinetic model of radionuclide accumulation in marine organisms can finally be developed. As the amount of ecological data increases, environmental predictive models should be developed to assess the radioecological consequences of the impact of nuclear power programs for time-intervals well beyond the time-range of an actual experiment. A simple model source-to-plant is nothing but the very first step in the development of a more complex model much needed to describe comprehensively the accumulation of radionuclides by marine organisms.

Pre-operational surverys in the vicinity of nuclear installations should enable a research team, as suggested earlier, to analyze, model and monitor the future behaviour of the radionuclides to be incorporated into the ecosystems surrounding nuclear installations. Unfortunately, ecological information gathered in one place may not be applicable in other places. However, much will be added to the experience with the consequences of radioactivity release from the nuclear power industry, if computer modelling of radionuclide accumulation becomes generally used.

REFERENCES

1. Evans, R.D. (1955) The Atomic Nucleus, McGraw Hill Book Company, Inc., New York, Toronto, London, 477.

2. Eberhardt, L.L. Modelling Radionuclides and Pesticides in Food Chains in Radionuclides in Ecosystems, (D. J. Nelson, editor), Proceedings of the Third National Symposium on Radioecology, May 10-12, 1971, Oak Ridge, Tennessee, U.S.A., CONF.- 7150501-P2, 894 (1971).

3. Reichle, D.E., P.B. Dunaway, and D.J. Nelson Turnover and Concentration of Radionuclides in Food Chains, Nuclear Safety 11, (1): 43(1970).

4. Polikarpov, G.G., Yu P. Zait ev, G. Barinov and V.P. Parchevsky (1967) General Features of the Concentration Processes of Radio active Substances by Hydrobionts in Different Seas of the World Ocean, in Radioecological Concentration Processes, Proceedings of an International Symposium held in Stockholm, 25-29, April, 1966 (B. Aberg and F.P. Hungate, editors), Pergamon Press, New York, 771.

5. Paschoa, A.S. (1975) The Natural Radiation Dose from Radium to Gammarus in the Hudson River, Ph.D. Thesis, New York Uni - versity.

6. Anonimous (1967) System/360 Continuous System Modelling Program User's Manual GH20-0367-04 IBM, White Plains, N.Y.

7. Anonimous (1972) System/360 Continuous System Modelling Program System Manual GY20-0111-00 IBM, White Plains, N.Y.

8. Ord-Smith, R.J. and J. Stephenson (1975) Computer Simulation of Continuous Systems Cambridge University Press, Cambridge.

9. Quintella, H.M. and D.G. Santimateo (1977) Introdução à Simulação Contínua: CSMP/360, PUC/RJ, Rio de Janeiro.

10. Nakahara, M., T. Koyanagi, and M. Saiki (1975) Concentration of Radioactive Cobalt by Seaweeds in Food Chain, in Impacts of Nuclear Releases into the Aquatic Environment, Proceedings of a Symposium, Otaniemi, 30 June - 4 July 1975, International Atomic Energy Agency.

11. Quintella, H.M. (1976) L.C.S.: Uma Alternativa para Modelagem de Levantamentos Estatísticos, Proceedings of Reunião Internacional de Estatística Aplicada, U.S.P., São Paulo.

12. Winkowski, J. Towards an Understanding of Computer Simulation, Polish Academy of Sciences, Rep. 243 (1976).

13. Klir, J., and M. Valach (1967) Cybernetic Modelling, ILIFFE, London and SNTL Prague.

APPENDIX

Integration Method

CSMP provides several methods of integration:

1. Fixed interval methods:
   - 1.a - ADAMS (second order)
   - 1.b - RKSFX (fourth order Runge-Kutta)
   - 1.c - SIMP (Simpson's rule)
   - 1.d - TRAPZ (trapezoidal)
   - 1.e - RECT (rectangular-Euler)

2. Variable interval methods:
   - 2.a - RKS (fourth order Runge-Kutta and Simpson's rule to estimate the error)
   - 2.b - MILNE (fifth order, predictor corrector)

In the present research RKS method was used throughout with satisfactory results. The package also provides the flexibility of accepting methods developed by the user when satisfactory results are not obtained with either of the methods provided.

In the CSMP, the RKS method computers the integral by means of the equation

$$Y_{t+\Delta t} = Y_t + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4),$$

where: $k_1 = \Delta t * f(t, Y_t)$

$$k_2 = \Delta t * f(t + \frac{\Delta t}{2}, Y_t + \frac{k_1}{2})$$

$$k_3 = \Delta t * f(t + \frac{\Delta t}{2}, Y_t + \frac{k_2}{2})$$

$$k_4 = \Delta t * f(t + \Delta t, Y_t + k_3)$$

The integration interval varies to satisfy the error criterion

$$\frac{|Y_{t+\Delta t} - Y^s|}{a + r|Y_{t+\Delta t}|} \leq 1$$

where Y^S is the term $Y_{t+\Delta t}$ computed by Simpson's rule, a is the absolute error and r is the relative error.