# GEORGIA INSTITUTE OF TECHNOLOGY

## The George W. Woodruff School of Mechanical Engineering

**Ph.D. Qualifiers Exam - Spring Quarter 1998**

Environmental Radiation Protection
EXAM AREA

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**Assigned Number (DO NOT SIGN YOUR NAME)**

- Please sign your name on the back of this page—

#4362

GEORGIA INSTITUTE OF TECHNOLOGY

**The George W. Woodruff School of Mechanical Engineering**

# Health Physics

## Ph.D. Qualifiers Exam

**Spring Quarter, 1998**

## Day 3

**Instructions**

1. Complete 4 of the 6 questions.
2. Use a separate page for each answer sheet (no front to back answers).
3. The question number should be shown on each answer sheet.
4. Staple your question sheet to your answer sheets and turn in.

**HP.Dav 3**

1. The angular distribution of the scattered photons from Compton scattering events is assumed to be isotropic for 1-MeV incident gamma photons. More specifically, the angular differential cross section for 1-MeV photons is described by

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}$$

where $r_0$ is the classical electron radius and is equal to 2.818 x $10^{-13}$ cm. The energy balance equation in a Compton scattering event is given by:

$$h\nu = h\nu' + E_e$$

and $$h\nu' = \frac{h\nu'}{1 + \frac{h\nu}{m_0 c^2}(1 - \cos\theta)}$$

Calculate the mass energy transfer cross section ($\sigma_{tr}/\rho$) in water due to Compton scattering interactions for 1-MeV photons.

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2. In carrying out maintenance on an accelerator, a worker is exposed to airborne tritium in water-vapor form for a period of 30 minutes. This exposure occurred beginning at 2:00 p.m. on a Friday. Starting at 8:00 a.m. on Monday the worker's urine was collected for 24 hours. The specific activity of tritium in the urine was 100 Bq $g^{-1}$. The effective energy per disintegration of tritium is 5.67 keV/dis. Estimate: (a) the concentration (Bq $m^{-3}$) of tritium in the atmosphere to which the worker was exposed, and (b) the soft-tissue dose equivalent ($S_v$) incurred as a result of the exposure. (Hint: use the attached metabolic data from ICRP-30 for hydrogen)

**(attach 4 sheets)**

# METABOLIC DATA FOR HYDROGEN

## 1. Metabolism

Data from Reference Man (ICRP, 1975)

| | |
|---|---|
| Hydrogen content of the body | 7 000 g |
| of soft tissue | 6 300 g |
| Daily intake of hydrogen | 350 g |
| Water content of the body | 42 000 g |
| Daily intake of water, including water of oxidation | 3 000 g |

For a number of soft tissues water comprises about 80% of the mass.

## 2. Metabolic Models

(a) *Elemental tritium*

As discussed in Chapter 8 of this report, exposure to elemental tritium in air is limited by consideration of the total dose equivalent received from tritium contained in the lung during any year of practice.

It is emphasized that the limit on exposure to tritiated water is more than four orders of magnitude less than that for elemental tritium and in most cases in practice exposure to tritiated water will be the limiting factor.

(b) *Tritiated water*

(i) *Ingestion.* Ingested tritiated water is assumed to be completely and instantaneously absorbed from the gastrointestinal tract and to mix rapidly with the total body water so that, at all times following ingestion, the concentration in sweat, sputum, urine, blood, insensible perspiration and expired water vapour is the same (Pinson and Langham, 1957).

(ii) *Inhalation.* Exposure to an atmosphere contaminated by tritiated water results in intake of that substance both by inhalation and by absorption through the intact skin.

Osborne (1966) has shown that exposure to an atmosphere contaminated by tritiated water at a concentration of $C$ Bq $m^{-3}$ results in the absorption of $10^{-2}$ $C$ Bq $min^{-1}$ through the intact skin. For Reference Man (ICRP, 1975) breathing air at a rate of 0.02 $m^3$ $min^{-1}$ the rate of inhaling tritiated water is $2 \times 10^{-2}$ $C$ Bq $min^{-1}$ and it is assumed that all of this is absorbed into body fluids. Therefore the total rate of absorption of tritiated water into body fluids is $3 \times 10^{-2}$ $C$ Bq $min^{-1}$ or $3.6 \times 10^3$ $C$ Bq in a working year of 2 000 h. It is assumed that this tritiated water is instantaneously distributed uniformly among all the soft tissues of the body.

(iii) *Distribution and retention.* Data on many humans have indicated that the retention of tritiated water is essentially described by a single exponential over the first months or more (Pinson and Langham, 1957). However, cases have been reported where a second exponential term or even a third have been observed (Snyder *et al.*, 1968; Sanders and Reinig, 1968; Moghissi *et al.*, 1972)

$$\text{i.e. } R(t) = A\, e^{-0.693t/T_1} + B\, e^{-0.693t/T_2} + C\, e^{-0.693t/T_3}$$

The value of $T_1$ is closely related to the turnover of body water. Since this is closely related to fluid intake, considerable variation of $T_1$ is to be expected because of variation of personal

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habits and ambient temperature (Wylie *et al.*, 1963; Butler and LeRoy, 1965). Values of $T_1$ have been observed in the range 4–18 days; a typical value is 10 days (Butler and LeRoy, 1965) and this is in agreement with the value obtained for Reference Man (ICRP, 1975) who has an intake of 3 000 g water per day and contains total body water of mass 42 000 g.

$$T_1 = 0.693 \times \frac{42\,000}{3\,000} \simeq 10 \text{ days}$$

The second and third exponential terms suggest the presence of tritium in compartments other than the body water, and indeed, organically bound tritium has been demonstrated in animals chronically exposed to tritiated water (Evans, 1969). However, it may be estimated from the data (Snyder *et al.*, 1968; Sanders and Reinig, 1968; Moghissi *et al.*, 1972) that such pools contribute of the order of 10% of the committed dose equivalent to the whole body deriving from an intake of tritiated water and they have been neglected in this report.

It is concluded that values of the committed dose equivalent to body tissues arising from an intake of tritiated water may be estimated from consideration of the retention of tritiated water alone. This view has been confirmed by several authors, e.g. Snyder *et al.* (1968) and Lambert and Clifton (1967).

Tritiated water is assumed to be uniformly distributed among all soft tissues at any time following intake and its retention to be described by a single exponential with a half-life of 10 days. Thus, the fraction of tritium, taken into the body as tritiated water, which is retained in the body $t$ days later, is given by

$$R(t) = \exp(-0.693t/10)$$

and the concentration in soft tissue, $C_s$ for a body content of $q$ Bq is given by

$$C_s = q/63\,000 \qquad \text{Bq g}^{-1}$$

where 63 000 g is the mass of soft tissues in the body of Reference Man (ICRP, 1975).

(c) *Organic compounds*

(i) *Ingestion.* When tritium-labelled organic compounds are ingested, a considerable fraction may be broken down in the gastrointestinal tract producing tritiated water. Organic compounds of tritium may also catabolize to tritiated water after they have crossed the gut.

In rodents, more than 90% of tritiated thymidine is broken down in the gastrointestinal tract and only about 2% of the ingested substance is actually incorporated into DNA (Lambert and Clifton, 1968). The fraction of tritium incorporated into DNA after ingestion of tritiated thymidine is about one-fifth of that after the direct entry of tritiated thymidine into blood (Feinendegen and Cronkite, 1977). The fractional absorption of other nucleic acid precursors and of most other tritiated compounds into the blood is not known; in most instances it is probably greater than that of tritiated thymidine.

(ii) *Inhalation.* Many organic compounds of tritium are not very volatile under normal circumstances and the probability of their being inhaled as vapours is, therefore, small. In circumstances where they might be inhaled it would be prudent to assume that once they enter the lungs they are instantaneously and completely translocated to blood without changing their chemical form.

(iii) *Distribution and retention.* Tritiated organic compounds which are metabolic precursors are usually distributed throughout the soft tissues and only rarely specifically concentrate in particular cells. A notable exception is tritiated thymidine which, if not catabolized, is

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taken up only by the nuclei of those cells synthesizing DNA. In mice, about 45% of all DNA-synthesizing cells in the body are located in the lining of the gastrointestinal tract, about 15% are found in the bone marrow and the rest are distributed mainly among spleen, lymphatic tissue, skin and parenchyma (Hughes *et al.*, 1964). These cells take up approximately 30% of the tritiated thymidine that enters the blood (Feinendegen *et al.*, 1973), and the clearance rate from the blood corresponds to a half-life of less than 1 h. Following ingestion, although the efficiency of incorporation of the compound is reduced by a factor of about 5, the relative distribution among the tissues and cells is considered to be similar to that after uptake from the blood (Feinendegen and Cronkite, 1977).

Some of the cells that incorporate tritiated thymidine into their DNA have a long life span of more than 10 days, renew themselves, and deliver a progeny of differentiated, functionally competent cells. It has been suggested that these are critical cells for the development of late radiation effects (Cronkite *et al.*, 1973).

Other tritiated compounds that serve as precursors for nucleic acids, are taken up in varying amounts by all nucleated cells in the body and thus become widely distributed throughout soft tissues. In mice these compounds were found to be incorporated from the blood into the tissues that contain large amounts of DNA-synthesizing cells less efficiently than tritiated thymidine (Feinendegen, 1978).

(iv) *Absorbed dose to tissues.* Average absorbed doses received by organs and tissues in experimental animals have been estimated for a number of organic compounds labelled with tritium; these include folic acid (Lambert and Clifton, 1967), thymidine (Lambert and Clifton, 1968), sex hormones (Vennart, 1969) and corticosteroids (Standeven and Clarke, 1967). Reports of these experiments were reviewed by Vennart (1969) who concluded that, under the radiological protection criteria then accepted, the maximum permissible annual intakes to blood of tritiated thymidine and tritiated folic acid should be about one-third of the maximum permissible annual intake of tritiated water, but that the maximum permissible annual intakes of tritiated sex hormones and tritiated corticosteroids should be about 30 times the maximum permissible annual intake of tritiated water. Consideration of absorbed dose to the cell nucleus (Berry *et al.*, 1966), of estimated biological effectiveness (Lambert, 1969; Bond and Feinendegen, 1966), and of the possibility that the long-lived self-renewing and DNA-synthesizing cells might be the critical cells (Feinendegen and Cronkite, 1977) indicate that the ALI to blood of tritiated thymidine should be about one-fourth to one-fiftieth of the ALI to blood of tritiated water. Furthermore the ALI by ingestion of tritiated thymidine might need to be one-tenth of that for tritiated water (Feinendegen and Cronkite, 1977).

In this report, specific values of ALI are not recommended for organic compounds of tritium but it is noted that they might differ considerably from those for tritiated water and that the value for tritiated thymidine might be as much as 50 times smaller. The exact ratio will depend on the compound and its route of entry into the body. This matter will be kept under review both with regard to any further indications of the relative effectiveness of these compounds as compared with tritiated water, and to their metabolism.

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Annual limits on intake, ALI(Bq) and derived air concentrations, DAC(Bq/m$^3$) (40 h/wk) for isotopes of hydrogen

| Radionuclide | | Oral | Inhalation |
|---|---|---|---|
| $^3H$ (Tritiated water) | ALI | $3 \times 10^9$ | $3 \times 10^9$ |
| | DAC | — | $8 \times 10^5$ |
| $^3H$ (Elemental tritium) | ALI | — | — |
| | DAC | — | $2 \times 10^{10}$ |

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**HP.Day 3**

3. (a) Assume that the absorbed dose in tissue irradiated with thermal neutrons is dominated by the $^{14}N(n,p)^{14}C$ reactions which has a cross section of 1.85 barns, and a Q value of 0.62 MeV. Calculate the averaged absorbed dose in 1 gram of tissue irradiated with a uniform thermal neutron fluence of $1.0 \times 10^{10}$ $cm^{-2}$.

(b) Assume that 1 gram of tissue contains $10^9$ biological cells and that a cell is killed if there is one or more $^{14}N(n,p)^{14}C$ reaction occur in it. Calculate the fraction of cells that are killed in the 1 gram of tissue in part (a).

Data: Tissue density = 1.0 $g/cm^3$, weight fractions = 10% H, 71.5% O, 15% C, and 3.5% N.

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4. Given an IV administered dose of 1 mCi of In-113m what is the whole body and gonad dose to a 70 kg reference man? Assume homogeneous distribution, no biological turnover (i.e. $T_{eff} = T_{phy}$) and that the gonads are the center of the source. In-133m has a 1.73 h half life. Known physical constraints are:

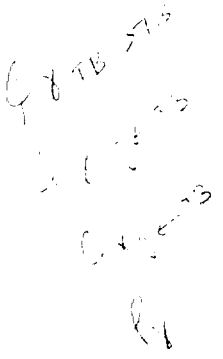
$$\gamma = 0.392\,MeV,\ {}^{\phi}\gamma_{TB\rightarrow TB} = 0.347,\ {}^{\phi}\gamma_{g\leftarrow TB} = 0.488,\ \rho_{\gamma} = 1$$

$$X = 0.028\,MeV,\ \phi_x = 0.784 \qquad {}^{\phi}x_{g\leftarrow TB_1} = 0.97$$

$$e/\gamma = 0.44,\ \omega = 0.85$$

Note: Formula for answer
(5 part Q – 2 points / part)

Calculate *n* value for *(γ, x, ic,* & Auger
Calculate Δ( for each value *(γ, x, np*
Calculate Concentration in μCi-hrs/g
Calculate whole body dose
Calculate gonad dose



**HP.Day 3**

5. If every fission product nuclide is assumed to emit a beta particle when it decays, then the activity in curies from F fissions at time t is

$$A(t) = 1.03\,(10^{-16})\,F\,t^{-1.2}\ Ci$$

where t is in days. If a reactor operates for 10 days at 250 kW:

a. What activity is present 1 day after its shut down?

b. Ten days later?

c. What fission products would be of importance after 100 days of decay? Name a few and list the concern.

$$(200\ MeV/fission;\ 1.6 \times 10^{-19}\ \ J = 1\,eV)$$

**HP.Day 3**

6. Human exposure to natural background radiation can be divided into 3 large classifications:

   a. What are they?

   b. Briefly describe each source of natural background radiation and its approximate contribution to the average individual's yearly dose.