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A REFORMULATION OF THE LUCAS HEIGHTS LIQUID EFFLUENT DISCHARGE AUTHORIZATION

by

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ABSTRACT

Liquid effluent containing low levels of radioactivity is discharged from the A.A.E.C. Research Establishment at Lucas Heights into a tidal estuary at the mouth of which are a number of commercial oyster leases. Since early 1961 the levels of release have been limited by a formula taking specific account of Ra–226, "other α emitters", Sr–90 and "other β emitters". This formula has worked well as is evidenced by the barely detectable levels of radioactivity coming from the Research Establishment found in environmental samples, but it had certain deficiencies and limitations which for operational reasons it became desirable to eliminate.

A new formula is described that is sufficiently general not to require future modification in principle and which incorporates recent data on estuarine dilution and concentration factors for nuclides in oysters, and which is based on current ICRP recommendations and N.S.W. State Regulations concerning maximum permissible doses applicable to members of the general public. Discharges are limited so that population exposures resulting from the ingestion of contaminated oysters, from sunbathing on sands near the discharge point, and from the incorporation of contaminated sand in cuts are kept within acceptable limits; it also ensures that people who daily handle large quantities of oysters will not be subjected to unacceptable levels of irradiation.

Values for maximum permissible monthly discharge (m.p.m.d.) for 173 nuclides have been calculated and tabulated. For mixtures of these nuclides the formula is:

$$\Sigma \frac{X_i}{(\text{m.p.m.d.})_i} \leqslant \frac{V}{3 \times 10^6} ,$$

where X_i is the quantity of the i^{th} nuclide released and V gallons is the monthly volume of liquid discharged or 3×10^6 gallons, whichever is the smaller.

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1. INTRODUCTION

Quantities of radioactivity that may be released from the A.A.E.C.'s Research Establishment at Lucas Heights into the Woronora Estuary in the form of liquid effluent are limited by a discharge formula which was first authorized by the Maritime Services Board and the N.S.W. Radiological Advisory Council early in 1961. The formula (Wilson 1959) is:

$$650\ Ra + 52\ (\text{other } \alpha \text{ emitters}) + 33\ (Ca + Sr) + (\text{all other } \beta \text{ emitters}) \leqslant \frac{V}{3 \times 10^6} \text{ curies/month,}$$

where, Ra is the radium content in curies,

other α is the remaining alpha emitter content in curies,

(Ca + Sr) is the combined radio-strontium and radio-calcium content in curies,

other β is the remaining beta emitter content in curies, and

V is the volume discharged over the month in gallons, or 3×10^6 gallons whichever is the smaller.

Since the first discharge on 11th April 1961, a number of circumstances have arisen which pointed to the need for a reformulation of the authorization and for a re-consideration of the levels of permissible discharge. The above formula has the following limitations:

(i) It was based on certain numerical factors and empirical data some of which have been superseded by more up-to-date information, for example, concentration factors for elements in marine organisms, the dilution capacity of the Woronora Estuary, and revised recommended levels of maximum permissible concentrations of radioactive nuclides applicable to the general population.

(ii) It is unnecessarily restrictive in the limits it imposes upon the discharge of a number of nuclides, in particular, tritium.

(iii) It unduly emphasizes the importance of Sr-90 and underestimates the toxicity of some other nuclides in the marine environment.

(iv) No account is taken of nuclides which emit substantially only γ rays.

(v) The need to conform to a monthly discharge limit is not justifiable. In considering the exposure of individual members of the population the ICRP (1964 para.43) permits the dose to be "accumulated at a rate that is determined by a maximum permissible annual dose This means that discharges and radionuclide concentrations in the environment need be balanced only over a twelve month period, rather than monthly. For administrative and control purposes, however, it may be convenient to operate on more frequent balances than this.

2. RATIONALE OF LIMITATION OF EFFLUENT DISCHARGE

The overriding reason for limiting the discharge of radioactivity into the environment is to ensure that exposure of the general public is kept within safe limits. Other considerations may in some circumstances become important: for example the effect of released activity on the flora and fauna itself, either directly or through its influence on delicately balanced ecological cycles; or the need to keep activity levels in the environment close to background lest they interfere with low level tracer experiments. In general, however, the recommended levels applicable to the exposure of humans are so low that if in inhabited areas human exposure is kept within safe limits, environmental levels will be satisfactory from other points of view.

There are two approaches to the problem of defining safe levels for the discharge of radioactive effluent into the environment. One may after a detailed study of the environment and the pathways leading to exposure of human beings, attempt to calculate the quantities of nuclides which may be released while keeping human exposures below agreed safe levels. Or one may adopt a more empirical approach by releasing conservative controlled quantities of activity for a given time (usually two to three years) and monitoring carefully the build-up of activity in the various critical exposure pathways, increasing the discharge, if desired, as each successive discharge level is proved acceptable. In practice both approaches should be followed because of the complexity of the processes by which radioactivity is dispersed and incorporated in the environment. The first years of any disposal programme should be regarded as largely experimental and the discharges and monitoring programme designed to yield as much information as possible about the quantitative behaviour of the various nuclides in the environment. This combined approach has been followed in the U.S.A. and the U.K. and has been recommended by the I.A.E.A. and the F.A.O.

The same rationale has informed the thinking on effluent disposal at Lucas Heights. All liquid effluent discharges have been carefully monitored since disposal into the Woronora Estuary began, both by the Effluent Control Laboratory and independently by an Effluent Audit Officer. At the same time the Woronora Estuary has been extensively surveyed to monitor the levels of activity appearing in a wide range of samples taken from it. The results of these two series of measurements are summarised in the following paragraphs. In general the levels of activity which has been released to the environment have been so low that in most samples it has been difficult to detect the presence of activity which could not be accounted for by naturally occurring radioactive nuclides and fallout from nuclear weapons tests.

3. COMPOSITION OF LIQUID EFFLUENT AT LUCAS HEIGHTS

The amount of activity released from the site in the form of liquid effluent is measured routinely by the Analytical Chemistry Section and checked independently by the Effluent Audit Officer. Analyses for total α and total β are made on each tank of effluent discharged whilst Ra-226 and Sr-90 determinations are carried out on monthly composite samples. The Effluent Audit Officer takes independent representative samples from all discharges and determines total α and total β on monthly composites and has Ra-226 and Sr-90 analyses done on quarterly composites which he prepares. He also makes weekly spot checks of total α and β in samples taken from the holding tanks before discharge, carries out gamma spectrometry on the quarterly composites and on samples from all discharges showing high β counts, analyses each monthly composite for tritium, and determines the amount of uranium discharged from quarterly composites. He reports these results quarterly (Todd 1961).

The estimated total activity discharged from the site to December 1965 taken from the Effluent Audit Reports is shown in Table 1. A number of observations can be made on the nature of the activity arising for disposal over this period:

(i) There is no significant amount of Ra-226 in the effluent.

(ii) The α activity would appear to be largely due to uranium.

(iii) In almost all cases the gross β activity discharged during a quarter can be accounted for by Sr-90 and the nuclides identified by γ spectrometry, apart from an average of about 5 mCi per quarter of unidentified β emitters. The known β activity can be detected with reasonable efficiency through a counter window about 2 mg/cm^2 thick but some of the unidentified activity is known to be due to low energy emitters. (Tritium is not included in this balance.)

(iv) Tritium, a very low energy β emitter requiring special counting techniques for its detection, arises from leaks in the heat exchangers of the reactor HIFAR. The amount appearing in the effluent varies considerably from month to month but averaged about 3 curies/month between January 1962 and December 1964. During 1965 the leak rate increased to about five times this value.

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(v) The volume of liquid discharged per quarter remained fairly constant at about 4×10^6 gallons until March 1964. Since then it has increased slightly to a mean quarterly discharge volume of about 4.7×10^6 gallons (2.1×10^{10} ml). The minimum detectable concentration in a sample and the corresponding minimum detectable discharge in a quarter (assuming a discharge volume of 2×10^{10} ml) is roughly:

	Min. Detectable Level μCi/ml	Min. Detectable Discharge per Quarter mCi
α	5×10^{-9}	0.1
Ra-226	1×10^{-9}	0.02
β	1.8×10^{-7}	3.6
Sr-90	1×10^{-8}	0.2

In reporting the quantities of activity discharged, a sample with no detectable activity is conservatively assumed to contain activity equal to the lower limit of detection.

(vi) The composition of the site effluent has not changed much in the past 5 years and consists almost entirely of mixed fission products, Co-60, tritium, and traces of activation products (for example Zn-65).

Mean monthly discharges have been of the order of:

Activity	Mean Monthly Discharge
Total α	0.1 mCi
Total hard β	6-7 mCi
consisting in part of:	
Sr-90	1-2 mCi
Cs-137	2-3 mCi
Co-60	0.5 mCi
Tritium	3 Ci
during 1965	9 Ci

If one excludes consideration of tritium (which is discussed below) it is clear, on the basis f these values, that there has been no difficulty in keeping within the limits set by the discharge ormula. At the current mean monthly discharge volume of about 1.5×10^6 gallons, the original ormula becomes:

$$650\ \text{Ra} + 52\ (\text{other } \alpha) + 33(\text{Ca} + \text{Sr}) + \text{other } \beta \leqslant 0.5 \text{ curies/month.}$$

ven if one assumes all α activity to have been due to Ra-226 and all β activity to have been r-90 one has:

$$(650 \times 0.0001) + (33 \times 0.0063) = 0.28\ ,$$

hich is less than the limit of 0.5.

It is clear, therefore, that the reason for revising the authorization is not specifically to enable greater quantities of activity to be discharged – in fact in the case of some nuclides the new formula imposes more restrictive discharge limits than exist at present – but to remove the inconsistencies and anomalies in the original formulation that are outlined in the introduction to this report.

4. RADIOACTIVITY IN THE WORONORA ESTUARY

There are three main pathways which could lead to the exposure of members of the general public from disposal of radioactivity into the Woronora Estuary. These are the ingestion of contaminated sea food, in particular, oysters; the incorporation in the body (for example in cuts) of sand contaminated with α emitters, and sunbathing on β-contaminated sand. The results of the past 5 years' measurements of radioactivity in Woronora oysters, fish, and sand are given in Tables 2, 3, and 4 (Giles and Stockdale 1966). In no case, except for the Zn-65 in oysters, is there any apparent increase in the activity of these samples over the 5 years; further, oysters from the Woronora Estuary are indistinguishable in radioactive content from the control oysters (from the Hawkesbury River) apart from the presence of Zn-65. In most cases the activities listed are just on the borderline of detectability and represent upper limits for contamination with naturally occurring radionuclides.

To put these measured environmental levels in perspective they are compared in the tables with representative maximum permissible concentrations in oyster flesh, fish, and sand. These concentrations are derived later in the report (Section 5) and represent levels which, under the assumed conditions of exposure, could lead to some members of the general public being irradiated at a rate which the ICRP recommends should not be exceeded. Maximum permissible concentrations in items of diet and other environmental samples calculated in this way are sometimes called "derived maximum permissible levels" or "derived working levels" to distinguish them from the maximum permissible concentrations in air or water recommended by the ICRP.

The following comments are relevant to Tables 2 and 4:

Table 2

(i) The relatively low gross α results for 1961 may be due to the time lapse between collection and counting of these samples, which amounted to 18 months in some cases. If some of the α activity is due to naturally occurring Po-210 ($T_{1/2}$ = 138 days), and there is some evidence for this, the low values are explicable.

(ii) The maximum permissible concentrations are derived assuming the consumption of 70 g of oysters per day and a maximum permissible daily intake of 1/30 that permitted by the ICRP to radiation workers. (See Section 5.1).

(iii) The maximum permissible concentration for gross β activity in oysters is not a well defined number; it depends on what nuclides are known not to be present. The value quoted in Table 2 is that applicable to Ca-45, Ru-106, Cs-134, and Ce-144 and assumes that Sr-90 is not present (or has been measured separately) and that I-126, I-129, I-131, Pb-210 (in equilibrium with its daughter products) and Ra-224 are not present in significant quantities.

(iv) The maximum permissible concentration of 10 $\mu\mu$Ci/g for unidentified α is somewhat arbitrary. It would be a conservative level provided Po-210 and Ra-226 are not present in significant quantities; it is also the value adopted by the U.K.A.E.A. for α activity in fish and shellfish at Dounreay.

(v) It is clear that as far as oyster contamination is concerned, even if one assumed that the α levels found were due entirely to the releases from Lucas Heights, α discharges could be increased by a factor of 50 (provided the composition of the effluent did not change) and β discharges by many orders of magnitude, before the maximum permissible levels are approached. It would also appear that Zn-65 releases could be increased some 10,000 times before the maximum permissible concentration is reached.

Table 4

(i) The maximum permissible concentration of α contamination in sand was estimated on the basis of a possible dose of 500 rem to a minute block of tissue if an α-contaminated grain of sand became lodged in a cut for 1 month; the maximum permissible concentration of β contamination in sand was estimated on the basis of a possible total skin dose of 3 rem to persons who sunbathe for 780 hr/yr on the contaminated sand.

(ii) The sand is sampled from small beaches along the banks of the estuary about 0.8, 2.9, and 3.7 miles from the discharge point. The activity in these sands is relatively high but has not yet been identified; it is all due to naturally occurring radionuclides. There is no significant difference between the activity levels in the sands from the beaches closest to and farthest from the discharge point, and there has been no increase in activity over the past 5 years.

Consequently the only unambiguous indication of activity in the Woronora Estuary in samples from the three main pathways that can be associated with discharges from Lucas Heights is the Zn-65 in oysters. Some Co-60 in a seaweed (zostera) collected about 1.5 miles from the discharge point, and Co-60 and mixed fission products in a filamentous weed (chlorophycean) growing at the discharge point have also been detected.

The results of an environmental survey to date indicate that, provided the general composition of the effluent does not change, discharges of α activity could be increased by some two orders of magnitude, whilst all β and γ activity could be increased at least 300 times before the corresponding maximum permissible concentrations would be approached. That is, about 10 mCi/month of undifferentiated α and 2 curies of undifferentiated β (not including tritium) could be released into the Woronora Estuary. These of course are underestimates of the quantities that could safely be discharged since in most cases they are based on the identification of barely measurable natural activity with activity originating from Lucas Heights.

5. MODIFICATION OF THE DISCHARGE AUTHORIZATION

Of all the conceivable pathways that could lead to the exposure of members of the general public to radiation as a result of releasing radioactivity into the Woronora Estuary, three stand out as significant. These are, as mentioned above, the eating of oysters containing radioactivity; the possibility of a grain of sand contaminated with activity getting into the body, particularly into cuts, and remaining there for some time; and sunbathing on sand which may have absorbed β emitting nuclides from the estuarine water.

These three pathways are now discussed in detail. In each case the problem of calculating safe discharge levels is based on three sets of assumptions which must be stated explicitly:

(i) The maximum level of exposure that is considered acceptable in each case.

(ii) Numbers defining an assumed level of intake or exposure time, for example, quantity of oysters eaten per week or the number of hours spent sunbathing per year.

(iii) Physical parameters entering into estimations of physical dilution, physical or biological concentration, and into the calculations of radiation dosage.

5.1 Ingestion of Oysters

(i) In considering the exposure of individual members of the population at large in situations where control over the exposure can be exercised, the ICRP in its recommendations revised in 1962 (ICRP 1964, para. 57), suggested that the maximum annual dose to the whole body or to the blood-forming organs should not exceed 0.5 rem. This would be achieved, in the case of a single nuclide for which the total body, the gonads, or the blood forming organs were the critical organ, if the average concentration of the nuclide in air or water were limited to 1/10 of the

maximum permissible concentration (mpc) listed for continuous (168 hr per week) occupational exposure in the ICRP Committee II report (ICRP 1959). However in situations such as that considered in this report, where an individual may be exposed to a mixture of nuclides a further reduction factor becomes necessary and for this the ICRP has recommended that 1/3 be taken (ICRP 1959. paras. 57, 68; 1964 para. 68). That is, the maximum permissible concentrations applicable to individual members of the population at large become, in this case, 1/30 $(mpc)^{168\ hr}$. This is also the definition of mpc "in relation to any other person" given in the N.S.W. Regulations to the Radioactive Substances Atc. 1957 as amended on 19th October 1962 (columns 3 and 4 of Schedule II).

From this one can derive the maximum permissible daily intake (m.p.d.i.) for a member of the general public for each of the listed nuclides by assuming a daily liquid intake of 2.2 litres. the value assumed by the ICRP in its derivations of maximum permissible concentrations in water. That is, the m.p.d.i. for a particular nuclide is given by,

$$\text{m.p.d.i.} = 2.2 \times 10^3 \times 1/30 (mpc)_w^{168\ hr} \ \mu Ci$$

where $(mpc)_w^{168\ hr}$ is the maximum permissible concentration in water for 168 hr per week exposure in units of μCi/ml. If the m.p.d.i. for known mixtures of radionuclides is estimated (by the method discussed in Section 6) on the basis of individual maximum permissible daily intakes limited in this way, the average annual total body dose should not exceed 0.5 rem (that is, about 5 times the background level in Sydney).

(ii) To assess the maximum permissible concentration of a nuclide in an item of diet one must assume a value for the quantity of that food eaten per day. In the case of oysters we assume a daily intake of 70 g. This is about a dozen large oysters per day compared with an estimated mean consumption rate among Sydney oyster eaters of about 4 doz./yr. Note that this is nearly 0.5 kg per week which is about one third of the normal protein requirement. The maximum permissible concentration of an individual nuclide in oyster flesh is thus:

$$(mpc)_{oys} = (1/70) \times (\text{m.p.d.i.}) \ \mu Ci/g .$$

(iii) Estimation of the concentration of a nuclide in oysters as a function of the quantity of activity discharged into the estuary requires a knowledge of two further factors; physical dilution occurring between the discharge point and the oyster beds and the extent to which different elements are concentrated by oysters from their environment. There is a considerable area of uncertainty surrounding both of these factors.

An extreme lower limit to the effective dilution which occurs in the Woronora Estuary between the discharge point and the oyster beds some 4½ miles down stream, can be obtained by comparing the level of Sr-90 found in oysters with the amount discharged. For about 3 years the monthly discharge of Sr-90 from the site averaged about 1.3 mCi in 0.6×10^{10} ml of effluent; the Sr-90 level in oysters (usually about 3 years old when harvested) is given in Table 2 as 0.002 $\mu\mu$Ci/g. Although it is known that this level is due to fallout from nuclear explosions, it can be used to put a lower bound to the dilution factor.

On the basis of measurements made at Lucas Heights of stable strontium ratios in oyster flesh and in estuarine water (L.E.Smythe, Unpublished). it is known that strontium is not preferentially concentrated in oyster flesh. Similar observations have been made elsewhere and one may confidently assume a concentration factor of 1 for strontium in oyster flesh. This then leads to an estimated lower limit of 110 for the dilution factor.

A similar estimate may be made on the basis of the Zn-65 figures. The quantity of Zn-65 discharged is very small and is known only imprecisely. There was however one period of about 18 months during which the mean discharge level was of the order of 0.2 mCi/month, and this led to a Zn-65 level in oysters of 0.15 $\mu\mu$Ci/g. The concentration factor for zinc in oysters is very high and is variously estimated to be between 10^4 and 10^5. Some measurements of stable zinc ratios in Woronora oysters and water have been made at Lucas Heights (L.E.Smythe. Unpublished) and give a concentration factor of 6×10^4. Using this value an estimated effective dilution factor

of 1.3×10^4 is obtained. It is difficult to give an estimate of error for this dilution factor, but the true value probably lies between 2×10^4 and 2×10^3. In what follows, a dilution factor of 10^3 is assumed to apply to effluent by the time it reaches the oyster beds.

The biological concentration factor that has been mentioned above is defined as the ratio:

$$C.F. = \frac{\text{concentration of element in material of interest}}{\text{concentration of element in estuarine water}} \quad \left(\frac{\mu Ci/g}{\mu Ci/ml}\right)$$

when equilibrium has been reached between the material and water. No attempt will be made to discuss the extremely complex physico-chemical and biological processes that lead to the adsorption of elements onto sands and silts in saline waters and the uptake of elements by marine organisms. The extent to which a radionuclide is accumulated by living material depends on the physical and chemical state of the nuclide, the presence of other substances dissolved in the water, particularly those of similar metabolic behaviour, the quantity of the element available for exchange through the ecosystem and the time taken for it to pass through the organism's food chain, the dispersion of the radionuclide through the pool of stable element, the season, as it affects the metabolism of the organism, the species of the organism itself, and no doubt many other factors.

In an estuarine system where the level of dissolved salts is not as constant as that in the open sea the situation is even more complex. The concept of *the* concentration factor of a particular nuclide in a particular organism is therefore somewhat fictitious and it is not surprising that such data as can be sifted from the literature are extremely variable. However since it appears that oysters, at least, concentrate to some extent almost every element it is most important to have some estimate, no matter how crude, of the magnitude of this accumulation.

The concentration factors used here for estimating the uptake of various elements in oysters are a judicious choice of values gathered from a number of sources (NAS-NRC 1957, 1959a, 1959b, 1962; I.A.E.A. 1963, Vinogradov 1953). Many of them have been estimated from the ratio of the concentrations of the stable elements in organism and sea water. Wherever possible, data applicable to oysters or molluscs were used; if these did not exist, values for invertebrates or fish were assumed. Failing this, values were inferred from information on metabolically similar elements; this was necessary in the case of ten elements.

With these three sets of data it is possible to estimate the quantity of each nuclide that could be released over a given period (say one month) at a regular discharge rate so that the $(mpc)_{oys}$ would not be exceeded. If Q curies is the maximum permissible monthly discharge of a given nuclide, and V gallons per month is the effluent discharge rate:

$$Q = \frac{2.2 \times 10^3}{W} \cdot \frac{(mpc)_w^{168\,hr}}{30} \cdot \frac{(V \times 4.55 \times 10^3)}{1} \cdot \frac{D.F.}{C.F.} \cdot 10^{-6} \text{ curies/month.}$$

where W = weight of contaminated food consumed per day in grams

(W = 70g in the case of oysters),

D.F. = dilution factor (D.F. = 10^3 in the Woronora Estuary at the oyster beds),

4.55×10^3 = number of ml per gallon,

and the remaining symbols have the meanings previously specified. Substituting the numerical values, and assuming a mean monthly discharge of 3×10^5 gallons:

$$Q = 1.43 \cdot (mpc)_w^{168hr} \cdot \frac{1}{C.F.} \cdot 10^7 \text{ curies/month.}$$

In using this formula the most restrictive listed value* of $(mpc)_w^{168hr}$ for soluble material is used.

* This choice is equivalent to using the values given in column 4 Schedule II of the Regulations to the N.S.W. Radioactive Substances Act (Revised 1962), where $(mpc)_w^{168\,hr}/30$ is listed for all ICRP nuclides.

Also no allowance has been made for radioactive decay or deposition of material in its travel from the discharge point to the mouth of the estuary. Since the mean flushing time of the estuary, although not known accurately, is probably of the order of a few days, this should introduce a considerable safety factor in the case of short-lived isotopes and certainly makes it unnecessary to consider nuclides with half lives shorter than one day.

The formula for the maximum permissible monthly discharge given above is applicable only if ingestion of oysters is the only pathway leading to exposure of the population. Further restrictions need to be imposed when wound contamination and sunbathing are considered.

5.2 Irradiation from Imbedded Particles

(i) No recommendations have been made by the ICRP or any other international or national body on the dose that can be permitted to minute volumes of soft tissue irradiated by individual α emitting particles imbedded in it. Although the present biological evidence is scanty and confused it is known that small volumes of soft tissue irradiated to very high doses (of the order of tens of thousands of rem) will heal rapidly without signs of hypertrophy or hyperplasia.

Another guide to an acceptable dosage level in this context is the practice at the U.S.A.E.C.'s Hanford Laboratories of permitting, in a radiation worker, a wound contamination of up to 0.004 μCi of Pu-239 (Norwood 1963). This could deliver a mean dose rate of the order of millions of rem per day to a volume of tissue about 35 μ in radius, if the particle is of high specific activity. The significance to be attached to such dosage calculations is however very much in doubt because of the minute volumes of tissue involved; we are considering here a mass of tissue of less than a millionth of a gram.

In view of this uncertainty the conservative dosage limit of 500 rem in 30 days is assumed to be applicable to this situation. This is equivalent to a wound contamination of about 0.4 $\mu\mu$Ci of Pu-239 (1/10,000 of that used as a guide at Hanford). It should also be compared with a maximum permissible *daily* intake via inhalation, applicable to members of the general public, of 6 $\mu\mu$Ci of insoluble Pu-239; this could well be in the form of relatively high specific activity particulates which would be expected to build up to an equilibrium lung burden of about 140 $\mu\mu$Ci.

(ii) It is assumed that sand along the banks of the Woronora Estuary may become contaminated with α emitting nuclides and that a grain of this sand becomes lodged in a cut and remains there for 30 days. Woronora sand is about 0.5 mm in diameter and there are roughly 10^4 grains per gram.

(iii) Since the closest beach is only about 0.8 miles from the discharge point a smaller value for the dilution factor is assumed than was taken in the case of the oyster beds. Based on an experimental investigation of dilution in the upper reaches of the estuary (Wilson 1959) a factor of 30 is used.

The exchange and absorptive capacities of the Woronora beach sands for α emitting elements from saline waters have not been measured in detail. However a concentration factor of 10^3 is assumed; the same figure was used as a basis for similar calculations in the derivation of the existing discharge formula (Wilson 1959).

The problem then is, what rate of release of α emitting activity at the discharge point will give a sufficient water concentration at the nearest beach to raise the activity of the sand to such a level that one grain containing contamination adsorbed to its surface when lodged in a piece of tissue for 30 days will deliver a dose of 500 rem?

(a) Dose rate from a grain of sand imbedded in tissue

Consider m $\mu\mu$Ci of α activity, of mean α energy 5 MeV adsorbed on the surface of a 0.5 mm diameter sand grain.

The dose rate to surrounding tissue is then:

$$D \cdot \frac{m \times 3.7 \times 10^{-7} \times 5 \times 1.6 \times 10^{-5} \times 3.6 \times 10^{4} \times 24 \times 30 \times 10}{2 \times 4\pi (0.025)^2 \ (0.0035) \times 100} \text{ rem/30 days}$$

$$\simeq 1.4\ m \times 10^{3} \text{ rem/30 days.}$$

In this the range of a 5 MeV α particle in tissue is taken as 35 microns and it is assumed that 50 per cent. of the emitted radiations are absorbed in the sand grain which is large relative to the α particle range. The relative biological efficiency(RBE) of α particles is taken as 10 in accordance with a recommendation of the ICRP. though little meaning can be attached to such an RBE in the present situation.

The activity per grain of sand necessary to give a dose of 500 rem in the assumed 30 day exposure is thus:

$$m = 0.36\ \mu\mu\text{Ci}.$$

(b) With 10^4 grains of sand per gram the maximum permissible specific activity of the sand becomes $3.6 \times 10^{-4}\ \mu$Ci/g. and the corresponding maximum permissible concentration of the estuarine water at that point. $3.6 \times 10^{-5}\ \mu$Ci/ml.

(c) The maximum permissible monthly discharge assuming a dilution factor of 30 and a monthly effluent volume of 3×10^6 gallons is thus:

$$Q_\alpha = 3.6 \times 10^{-5} \times (3 \times 10^{6} \times 4.55 \times 10^{3}) \times 30\ \mu\text{Ci/month.}$$

$$= 1.47 \text{ Ci/month.}$$

This discharge level for α emitters is about 75 times that permitted for other alpha emitters under the existing discharge formula due to the increase in permitted tissue dose from 50 rem to 500 rem and a more realistic model being used to estimate the dose in which a larger volume of tissue was assumed through which the dose was averaged.

Thus if the possibility of contaminated sand becoming incorporated in the body were the sole source of exposure of the general public. the discharge of all α emitters from the site would not exceed about 1.5 curies per month. The discharge of many α emitters will however be restricted to levels considerably below this owing to the limitation imposed by the possibility of eating contaminated sea food.

5.3 Sunbathing on Contaminated Sand

(i) In the case of a person lying on contaminated sand the beta dose rate to the skin will impose the maximum restriction on the contamination level. Alpha emitters need not be considered since the most energetic α particles do not penetrate the epidermis and the body dose from γ emitters is negligible if surface beta dose rates are limited to acceptable levels.

Following the 1962 ICRP recommendations. the external skin dose that a member of the general public receives should be limited to a total absorbed dose of 3 rem in a year (ICRP 1964 paras. 52a. 57a). To allow for the possible case of a person receiving also the maximum permissible whole body dose of 0.5 rem, the maximum permissible skin dose is taken as 2.5 rem per year. The skin dose is the absorbed dose estimated for a depth of 7 mg/cm^2.

(ii) To compute the annual dose to the skin an average exposure time of 15 hr/wk (780 hr/yr) is assumed as was done in the derivation of the existing formula. This is a surface dose rate of $\left(\frac{2.5}{780} \times 1000\right) = 3.2$ mrem/hr.

(i) The same factors for dilution and absorptive capacities for the Woronora sands are assumed as was done in the case of contamination of the sand by the heavier element α emitters. That is, the concentration of activity in the water at the nearest beach to the discharge point is 1/30 of the discharge concentration and the ratio of the concentration of activity in the sand per unit mass to that in the water is taken as 1000.

To estimate the dose rate to the skin of a person lying on the contaminated sand it is sufficient to assume that this dose is equal to half that delivered within a large uniformly contaminated volume of sand corrected for the different electron stopping powers of tissue and sand, and making due allowance for absorption in the top 7 mg/cm^2 of skin. the depth at which the ICRP recommends that "skin dose be calculated (ICRP 1955). That is:

$$\text{Skin dose } D = (1/2)D_\infty \times R_{t,s} \times f$$

where D_∞ = the absorbed dose rate in a large volume of uniformly contaminated sand.

$R_{t,s}$ = the ratio of the stopping powers of tissue and sand for electrons. and

f = the fraction of the surface dose at a depth of 7 mg/cm^2.

D_∞ is easily calculated and is given by

$$D_\infty = \frac{C \times 3.7 \times 10^4 \times \bar{E} \times 1.6 \times 10^{-6} \times 3.6 \times 10^2}{10^7} \text{ rem/hr}$$

$$= 2.13\, C\, \bar{E} \text{ rem/hr}$$

where C = concentration of activity in the sand in μCi/g

$\bar{E}$ = the mean energy of the emitted β particles in MeV.

$R_{t,s}$ may be estimated from published values of electron stopping powers (Nelms 1958). It is a slowly varying function of energy and is equal (to within ± 5 per cent.) to 1.26 for energies between 0.04 MeV and 1 MeV. The absorption factor is very much more energy dependent varying from about 0.03 to 0.93 in the same energy range (Henriques 1952 Fry 1964). Thus $D \simeq 1.3\, \bar{E}\, f\, C$ rem/hr. which must not exceed 3.2 mrem/hr.

Then the assumption of an estuarine dilution factor of 30 and a sand absorption concentration factor of 10^3 gives, for a monthly volume discharge of 3×10^6 galls. a maximum permissible monthly discharge, Q_β, of:

$$Q_\beta = \frac{1.0}{\bar{E}\, f} \text{ curies.}$$

For the most energetic β emitter, and therefore the most hazardous, (with half life exceeding one day). $\bar{E}$ is about 1 MeV and $f = 0.94$. Thus the minimum value of Q_β is about 1 curie/month, that is, no β emitter need be restricted to a mean monthly discharge of less than 1 curie to keep population exposure from sunbathing within acceptable limits. In most cases the imposed limit due to the possible ingestion of oysters is more restrictive than that due to sunbathing.

5.4 Other Possible Limitations on Discharge

5.4.1 Dose due to swimming in estuary

The β dose rate due to immersion in water containing C_w μCi/ml is calculated in the same way as the sunbathing dose. It is:

$$D_w \quad 1.07\, C_w\, \bar{E}\, f \text{ rem/hr.}$$

The ratio of immersion dose to sunbathing dose assuming the same exposure time in each case is:

$$\frac{D_w}{D_s} = \frac{1.07}{1.3} \times \frac{C_w}{C_s} \simeq 10^{-3}$$

since the ratio C_w/C_s has been assumed to be 10^{-3}. Thus if discharges are limited to keep exposure from sunbathing safe, exposure from swimming will be safer by a factor of some 1000.

5.4.2 Dose rate to oysters

Owing to the high dose rates that are possible from α activity distributed throughout oyster flesh it is of interest to see if any limitation on discharge is required to protect the oysters themselves. In an oyster (or any organism for that matter) containing a uniform distribution of α activity of C $\mu\mu$Ci/g the absorbed dose rate, assuming an RBE of 10 is:

$$D = \frac{C \times 2.2 \times E \times 1.6 \times 10^{-5} \times 60 \times 24 \times 365 \times 10}{100} \text{ rem/yr.}$$

$$= 0.185\ E\ C \text{ rem/yr.}$$

$$= C \text{ rem/yr} \quad \text{for} \quad E = 5.4 \text{ MeV.}$$

The 50 per cent. lethal dose for molluscs is 5,000 – 20,000 R for acute exposure (Wallausckek and Lützen 1964) so there is no possibility of any significant somatic damage to oysters at the levels of activity that would be safe for human consumption. No information can be found concerning the genetic effects of radiation on oysters but it would seem very conservative to allow a dose of the order of 100 rem over the life-time of the oyster, namely 3 years, that is, a dose rate of about 30 rem/yr. This would limit the concentration of α activity in the oyster to 3×10^{-5} μCi/g which is larger than any permitted α level based on ingestion.

Permissible β contamination in oysters from this point of view would be some 50 times the α figure because of the lower value of E (maximum $\bar{E}$ is about 1 MeV) and the RBE of β particles being 1 instead of 10. That is, β levels in oysters should not exceed about 1.5×10^{-3} μCi/g which again is larger than any permitted β level based on ingestion.

5.4.3 External dose rate from contaminated oysters

The possible irradiation of persons handling oysters, or working near a considerable accumulation of oysters, is now investigated to ensure that any such exposures are within acceptable limits.

(i) External gamma dose rate

Consider first the exposure that a person might receive if he worked for significant periods close to a number of bags of oysters containing gamma emitting radioactivity. Because in this case activity which may be accumulated in oyster shell must be taken into account, some further reductions in permitted monthly discharges may be necessary. The exposure model assumed is that of an oyster opener working continuously one foot from a pile of bags of oysters which have been grown in water containing a gamma activity of C_γ μCi/ml. Since the gamma exposure rate does not depend critically on the arrangement of the bags, nor the total number of oysters involved (an increase in total activity being partially compensated for by an increase in absorption of the gamma rays within the oysters), a pile of 10 bags, each containing 100 dozen oysters, stacked in a close-packed fashion is assumed: this would give a roughly spherical volume about 3 ft in diameter.

The maximum permissible exposure rate applicable to such a person, being a member of the general public, is 0.5 rem/yr. To allow for the contingency that he may also consume 1 doz. oysters per day contaminated at the maximum permissible level derived in Section 5.1, the permitted external whole body exposure rate is reduced to (0.5 – 0.17) rem/yr. or about 0.15 mR/hr for a 40 hr/wk, 50 wk/yr exposure. Actually it is known that at any oyster collection centre in the Sutherland area, oysters from the Woronora Estuary account for only about 1/10 of the total number handled. The maximum permissible exposure rate could therefore legitimately be raised to 1.5 mR/hr. This is not done in these estimates and the safety factor of 10 is retained.

If the total activity within the 3 ft diameter pile (radius ~ 45 cm) is A mCi, and the specific gamma ray constant of the contaminating nuclide is Γ mR/hr at 100 cm per mCi, the exposure rate at one foot (~ 30 cm) from the surface of the pile is given by:

$$X = A\Gamma \times \left(\frac{100}{75}\right)^2 \times \phi \quad \text{mR/hr.}$$

where ϕ is a factor which takes account of absorption of gamma rays within the pile. To calculate ϕ it is assumed conservatively that all gamma rays have an energy of 1.3 MeV; this leads to a linear attenuation coefficient of about 0.06 cm^{-1} for the mixture of shell and flesh within the pile of oysters. With this assumption, $\phi = 0.28$, and:

$$X = 0.5\ A\Gamma \quad \text{mR/hr, which must be} \leq 0.15$$

That is, $$A \leq 0.3/\Gamma \quad \text{mCi.}$$

To calculate A one must know the extent to which nuclides are concentrated in oyster shell, as well as flesh. Each oyster is assumed to consist of 7g of flesh and 30g of shell; that is, within the 10 bags (12,000 oysters) there is a total of 84 kg of flesh and 360 kg of shell. Thus, if the concentration factors for a given nuclide in shell and flesh are CF_s and CF_f respectively:

$$A = C_\gamma (84\ CF_f + 360\ CF_s) \quad \text{mCi ,}$$

where C_γ in μCi/ml is the concentration of the nuclide in the water in which the oyster has grown. Assuming once again a monthly volume discharge of 1.4×10^7 ml and a dilution factor of 10^3 at the oyster beds, the total monthly discharge Q_γ is given by:

$$Q_\gamma = 1.4 \times 10^7\ C_\gamma \text{ Ci/month, and:}$$

$$A = \frac{Q_\gamma}{1.4 \times 10^7} \times 84\ CF_f(1 + 4.3\ CF_s/CF_f) \quad \text{mCi .}$$

Combining this with the restriction that $A \leq 0.3/\Gamma$, we have finally:

$$Q_\gamma \leq \frac{5.0 \times 10^7}{\Gamma\ CF_f(1 + 4.3\ CF_s/CF_f)} \quad \text{Ci/month.}$$

The implications of this limitation are discussed in Section 6.1 where it is shown that it imposes a further restriction on the discharge of certain nuclides.

(ii) External beta dose rate

Surface β dose rates to the hands of oyster openers will be well within acceptable levels. Although no recommendations exist for maximum permissible dose rates to the hands of members of the general public, a figure of 1/10 that permitted to radiation workers may be taken as a protection guide; this is in line with ICRP practice. That is, the skin dose to the hands of oyster openers must be kept below 7.5 rem/yr, or 3.7 mrem/hr for a 40 hr/wk, 50 wk/yr exposure.

An estimate of the maximum surface β dose rate to be expected from oyster shell may be obtained from a comparison of the dose rate limit imposed for beach sands. The discharge of β emitters has been limited so that the β dose rate to the skin of a sunbather cannot exceed 3.2 mrem/hr. This calculation was based on a dilution factor of 30, and a mean concentration factor of 10^3 for nuclides in sand. Assuming the same mean concentration factor for β emitting nuclides in oyster shell, the skin dose rate from oyster shell taken from an area where the dilution factor is 10^3 (that is, about 33 times that at the beach sands) is expected not to exceed $\frac{3.2}{33} \simeq 0.1$ mrem/hr.

The actual biologically significant skin dose an oyster opener would receive during a year would be very much less than that indicated by this dose rate. As mentioned above, only 1/10 of the oysters handled will come from the Woronora Estuary. Also the skin on the palms of the hands is about 10 times the thickness of 7 mg/cm^2 assumed in the calculation of the sunbathing dose rate; this would lead to a reduction in the dose received by the cells in the basal layer of the epidermis by a factor which depends on the energy of the β rays but which is between 5 and 300 for maximum beta energies in the range of 1 to 0.4 MeV. The skin dose due to the handling of contaminated oysters is therefore expected to be less than that received from background radiation in the Sydney area (about 80 mrem/yr).

Thus, apart from the need to restrict further the discharge of certain gamma emitting nuclides, no other restrictions arise from the discussions in this section.

6. PERMISSIBLE LEVELS OF DISCHARGE

6.1 Individual Nuclides

Permissible levels of discharge for individual nuclides estimated on the basis of ingestion of oysters alone are set out in Table 5. This table lists the maximum permissible estuarine water concentration, $(mpc)_{est}$ and the maximum permissible monthly discharge, (m.p.m.d.) for all nuclides having half lives greater than 1 day and considered by the ICRP in its 1959 recommendations; there are 173 of these. The concentration factors used have been discussed above and refer wherever possible to oysters, molluscs, or as a last resort to marine invertebrates. The asterisked values refer to radioisotopes for which no information at all is available for guidance and for which approximations have been made after consideration of the concentration factors for metabolically and chemically similar elements. Permissible monthly discharges have been worked out for a monthly release of 3×10^5 gallons and a mean dilution factor at the oyster beds of 10^3, as discussed in Section 5.1.

This listing must now be modified to take account of the limits imposed by wound contamination, sunbathing, and external gamma irradiation in accordance with the discussions in 5.2, 5.3 and 5.4.3 above. Thus no α emitter is to be discharged at a rate exceeding 1.5 Ci/month; 15 nuclides (Nd-144; Sm-147; Ra-223, 224, Th-227, 231; U-230, 233, 234, 235, 236, 238 and natural uranium; Cm-242; and Bk-249) are affected by this limit. Also no β emitter is to be released at a monthly rate exceeding $(\frac{1.0}{E\,f})$ curies which restricts further the m.p.m.d. of 28 nuclides listed in Table 5; These nuclides with their modified values of m.p.m.d. in curies are, Y-90(1.2), Sr-90(1.2), Cd-115m-115(1.4) Rb-86(1.6), Ce-141(1.8), Ba-140(1.8), Sr-89(2.0), Y-91(2.0), Ho-116(2.0), Te-129m-219(2.1), Sb-122(2.3), La-140(2.5), Cs-137(2.8), Ce-143(3.1), Nd-147(3.4), Ag-111(3.5), Pm-149(3.5), Ca-47(3.8), Pr-143(4.1), Tm-170(4.1), Os-193(4.1), Cl-36(5.0), As-74(5.7), Te-127m-217(5.7), Na-22(8.3), Br-82(11), Cs-136(19), and S-35(160).

To calculate the m.p.m.d. of gamma emitters, Q_γ, the concentration factors, CF_s, for elements in oyster shell must be known. From the literature, mainly Vinogradov (1953), and from some analyses done at Lucas Heights, shell concentration factors for Be (3×10^3), Ca(10^5), Fe(2×10^4), Sr(200), and Ba(400) are reasonably well known, and we have some guide to the values for Na(1), Cr(4×10^4), Mn(2×10^4), Co(4×10^3), and Br(100). For the rest, in the face of a total lack of information, it is assumed that the concentration factor for shell is equal to that for flesh. With these values of CF_s, and the flesh concentration factors listed in Table 5, Q_γ may be calculated. Thirteen nuclides have a Q_γ which is smaller than the imposed limits for ingestion or sunbathing; these, together with their new values of m.p.m.d. in curies are, Mn-52(0.28), W-187(0.32), Fe-59(0.8), Mn-54(1.1), Co-60(2.1), Co-58(5.1), Cr-51(14), Co-57(31), Bi-206(105), Be-7(128), Sb-125(131), Pt-193m(135), and Sr-85(194).

A final adjustment is made to the individual discharge limits as computed so far. Many of the values of m.p.m.d. for the less hazardous nuclides are quite high (of the order of hundreds or even thousands of curies), much in excess of any foreseeable need at Lucas Heights.

Therefore a maximum of 100 curies is set for the m.p.m.d. of all nuclides with the exception of tritium, for which a limit of 1000 curies per month is suggested. This limit for tritium is still a factor of 430 less than the calculated m.p.m.d. listed in Table 5.

The amended list of mean monthly discharge limits for individual nuclides is given in Tables 6 and 7. Each nuclide may be released at the listed discharge rate provided it is the only nuclide present, and provided also that members of the public are not subjected to other sources of exposure due to the operation of the Research Establishment. There are, in fact, no such additional sources of exposure originating from Lucas Heights.

6.2 Mixtures of Nuclides

If, as is usually the case, the effluent consists of a mixture of nuclides, the dose contribution from each must be considered, so that the total dose to each critical organ does not exceed the maximum permissible population exposure levels assumed in these calculations. In such cases as this the ICRP recommends that the whole body be considered the critical organ, and it was for this reason that $1/30(\text{mpc})^{168\,\text{hr}}$ was recommended as a basis for planning discharges, rather than $1/10(\text{mpc})^{168\,\text{hr}}$, which would have been sufficient if one were considering the exposure of a single organ in individual members of the general public. Because this lower value has been assumed in these calculations the effect of additivity of dose may be simply accounted for by limiting the mean monthly activity release so that:

$$\Sigma_i \frac{X_i}{(\text{m.p.m.d.})_i} \leq \frac{V}{3 \times 10^6}$$

where X_i = the quantity of the i^{th} nuclide discharged during the month (curies),

$(\text{m.p.m.d.})_i$ = the permissible monthly discharge of the i^{th} nuclide as listed in Tables 6 and 7 (curies), and

V = the volume of effluent discharged over the month (gallons), or 3×10^6, whichever is the smaller.

The formula is completely general and other nuclides not at present in the existing lists may be included if their permissible monthly discharges are estimated according to the procedures laid down in this report. This will of course require a calculation from first principles of the maximum permissible daily intake appropriate to each nuclide since all nuclides (with half lives greater than 1 day) considered by the ICRP have been included in the present tables.

It should also be permissible to make adjustments to the values listed in Tables 6 and 7 in the light of any new data which become available on, for example, concentration factors, dilution factors, etc.

7. OPERATION WITHIN THE FORMULA

Although at first sight this formula may appear too complex for the routine control of effluent disposal, in practice it need involve little more work and analysis than is required to administer the previous formula. In fact at current levels of discharge, less analysis would be involved than is being done at present. The formula is such that the more activity one wishes to discharge the more analyses one must do to prove the discharge levels safe.

The first thing to be pointed out is that although the formula includes explicitly a large number of nuclides, it does not require that determinations be made for all nuclides individually. Indeed, in many cases it may not be necessary to do any specific analyses at all, and rarely will the occasion arise when knowledge of the levels of more than a few nuclides is needed. If one can work within mean monthly discharges equal to the most restrictive listed in Table 7 (namely 10 mCi for α activity and 29 mCi for β activity) there is no need to do any analyses apart from the determination of total α and total β activity*. The formula in this case becomes $\frac{\alpha}{10} + \frac{\beta}{29} < \frac{V}{3 \times 10^6}$ where

*Total beta counting should be done with a windowless or thin window ($\sim 100\ \mu g/cm^2$) low background counter so that all beta emitters with energies down to Ni-63, that is, about 0.06 MeV, are counted with reasonable efficiency. (Ni-63 emits the softest β radiation of all the nuclides listed apart from tritium). High efficiency in the counting of soft β emitters is, however, not required. For example the most restrictive m.p.m.d. for a soft β emitter ($E_{max} < 0.22$ MeV) is 8.6 Ci for Ni-63. When working at an m.p.m.d. for total β of 29 mCi, an efficiency of detection

continued as footnote p.15

α and β are the gross α and gross β activities (in units of mCi) in a month's discharge.

Up to the present time the Research Establishment could have worked very comfortably within this limitation if the term for tritium were included. In paragraph 2 the mean monthly discharge over the past 5 years is given as 0.1 mCi of α, 7 mCi of β and 3 Ci of tritium. The left hand side of the formula then becomes:

$$\frac{0.1}{10} + \frac{7}{29} + \frac{3}{1000} = 0.25 \quad ,$$

which is less than the limit of 0.5 applicable to a monthly volume discharge of 1.5×10^6 gallons. Actually, the composition of the effluent is known in finer detail than this; analyses have been performed for Sr-90 and gamma spectroscopy has enabled levels of Cs-137 and Co-60 to be determined. The unknown β activity therefore amounts to only 1.5 mCi, and since this may have been In-114m-114, discharge must be limited to the m.p.m.d. for this nuclide, namely 29 mCi. Including these nuclides explicitly in the formula gives, for the left hand side:

$$\left(\frac{0.1}{10}\right)_{\alpha} + \left(\frac{0.002}{1.2}\right)_{\text{Sr-90}} + \left(\frac{0.003}{2.8}\right)_{\text{Cs-137}} + \left(\frac{0.0005}{2.1}\right)_{\text{Co-60}} + \left(\frac{1.5}{29}\right)_{\beta} + \left(\frac{3}{1000}\right)_{\text{H-3}} = 0.07 .$$

The greater detail has allowed a greater potential for the discharge of other activity, for example Zn-65, which during one quarter averaged 1 mCi/month; this would contribute 1/95 = 0.01 to the sum.

This in general is the way the formula is expected to work. The discharge of the unknown fraction of the effluent activity is limited to a level defined by the most restrictive nuclide not known to occur in the effluent. If analyses for indium and phosphorus had shown In-114m-114 and P-32 not to be present ** and Ra-228 (in equilibrium with Ac-228) was not revealed in the gamma spectrum of the effluent, the next most restrictive β emitter would be W-185 and the m.p.m.d. for unknown β emitters could be taken as 0.14 curies. (In-115 may be neglected; because of its enormous half life of 6×10^{14} years its specific activity is so low that the m.p.m.d. of 0.13 Ci amounts to some 2×10^4 tons!).

As pointed out above, the unknown β emitting fraction of the effluent is expected to be small since gamma spectrometry alone will be able to identify some of the beta emitters present. In general if one is seeking to increase discharge levels it will prove simpler to analyse specifically for one or two of the major nuclides known to be present, thereby reducing the unknown fraction, than to eliminate systematically the more restrictive nuclides in an attempt to increase the m.p.m.d. for unknown emitters.

The same considerations apply, of course, to α emitters. Gross α activity must be limited to a mean monthly discharge of 10 mCi unless it can be proved that Po-210 is not present. The limit then becomes that appropriate to Ra-226, namely 29 mCi, and if that is not present, then 0.13 curies corresponding to Pa-231.

** Detection methods will in general only prove that a nuclide is not present at a level exceeding some minimum detectable level. It will always be assumed that, if "undetectable", the nuclide is present at this minimum detectable level. This of course applies equally to the determination of total α and total β.

* continued from footnote p.14

for Ni-63 of 0.34 per cent. would be sufficient to ensure that the discharge of this nuclide remained within prescribed limits. By the same token some economy in discharge potential could be effected if, when counting soft betas with reasonable efficiency, a separation of the activity into hard ($E_{max} > 0.22$ MeV) and soft betas is made by re-counting the sample through an appropriate filter. Hard beta could then be discharged at a maximum rate of 29 mCi per month with allowance for the soft beta component being made on the basis of an m.p.m.d. of 8.6 curies. Tritium will not of course be included in total beta determined in this way. It is most conveniently measured by liquid scintillation counting.

8. SUMMARY AND CONCLUSIONS

The amount of radioactivity that can be released from Lucas Heights in the form of liquid effluent has hitherto been limited by an authorization that came into force at the beginning of 1961.

The authorization was conceived and approved in the knowledge that it would be applied and interpreted on the commonly used basis of β-measurements made with thin-window Geiger tubes. Accordingly, the authorization as operated has not taken quantitative account of the discharge of the relatively harmless soft β emitters such as tritium. This nuclide, which emits such soft β rays that special counting techniques are required for its detection, is produced in large quantities in the D_2O moderator of the reactor HIFAR some of which escapes through small leaks in heat exchangers and finds its way into the site liquid effluent.

Although of little biological significance tritium has to date constituted the major proportion of the β contamination in the effluent. It therefore seemed worth while to revise the discharge formula in such a way as to take quantitative account of soft β emitters whilst at the same time recognizing their relatively low hazard.

It was also desirable to produce a formula that was sufficiently general not to require a fundamental reformulation despite significant changes that might occur in the composition of the effluent arising at Lucas Heights. At the same time the opportunity was taken to revise some of the calculations upon which the original formula was based and to amend some of the permissible levels employed in the light of more recent recommendations.

The model that is used to estimate permissible discharge rates is similar to that upon which the original formula was based. Radioactivity released into the Woronora Estuary is assumed to be diluted by eddy diffusion and tidal flushing and carried to the oyster beds at the mouth of the Estuary some 4½ miles away. On the way it washes through small deposits of sand on the banks where people sometimes swim and sunbathe: the nearest such beach is about 0.8 miles from the discharge point.

Mean equilibrium dilution within the upper mile and a half of estuary has been experimentally measured at not less than 30 and this value is used to estimate the level of beach sand contamination as a function of activity released. No direct measurement of dilution at the oyster beds has been made but the order of magnitude of its effective value may be estimated from observed levels of Sr-90 and Zn-65 in Woronora oysters, since the quantity of these nuclides discharged from the site is known. Effective dilution based on the Sr-90 values is 110; this is an extreme lower limit since it is known that by far the major part of the Sr-90 measured in Woronora oysters is due to fallout from nuclear weapons tests and not to effluent released from the site. A more realistic value of 10^3 is given by the Zn-65 measurements. (These estimates are based on measured biological concentration factors of 1 and 6×10^3 for strontium and zinc, respectively in Woronora oyster flesh). On the basis of these figures a working value of 10^3 is assumed for effective dilution at the oyster beds.

Activity reaching the oyster beds is concentrated in oyster flesh by a factor depending, amongst other things, on the chemical nature of the nuclide; these factors vary between 1 and 10^5 and have been mostly taken from the literature. The concentration of radioactivity in the beach sands relative to that in the estuarine water is assumed to be 10^2 for all nuclides. The level of activity in oysters and in the sands may then be calculated as a function of the activity in the water.

Radioactivity released into the Woronora Estuary is assumed to lead to exposure of members of the general public by three major pathways: ingestion of contaminated sea-food (in particular oysters), the incorporation in the body (for example, in cuts) of sand contaminated with alpha activity, and sunbathing on sand containing β emitting nuclides. The exposure of persons handling large numbers of oysters has also been taken into account. To estimate the mean dose which could be received from eating contaminated oysters, a daily consumption of 70g (that is, about 1 doz. large oysters) is assumed. In the case of wound contamination it is assumed that the α active sand grain remains in contact with tissue for 1 month, whilst exposure at the rate of 15 hr/week is assumed in the estimation of skin dose from sunbathing.

Finally, maximum permissible rates of discharge are estimated so that mean dose rates to individual members of the general public are kept within the following limits:

In the case of whole body exposure (or exposure to mixtures of nuclides): 0.5 rem per year;

External skin dose: 3 rem per year;

Wound contamination: 500 rem to a minute mass (approximately 30 μg) of tissue in 1 month. (This is the dose rate due to about 0.4 $\mu\mu$Ci of 5 MeV alphas imbedded in tissue).

The results of the calculation are expressed in terms of a maximum permissible monthly discharge (m.p.m.d.) rate for each nuclide assuming a monthly volume discharge of 3×10^6 gallons. In practice only nuclides having half lives longer than 1 day and listed by the ICRP in its 1959 recommendations have been considered, but in principle all nuclides could have been included. These values of m.p.m.d. for individual nuclides have been tabulated.

In the general case of the discharge of mixtures of nuclides in radioactive liquid effluent from Lucas Heights into the Woronora Estuary, the following formula defines the limiting mean monthly discharge rate:

$$\Sigma_i \frac{X_i}{(\text{m.p.m.d.})_i} \leqslant \frac{V}{3 \times 10^6} .$$

where X_i = the quantity of the i^{th} nuclide discharged during the month (curies),

$(\text{m.p.m.d.})_i$ = the permissible monthly discharge of the i^{th} nuclide (curies) as given in Tables 6 and 7, and

V = the volume of effluent discharged over the month, or 3×10^6, whichever is the smaller (gallons).

The formula and operation within it are to be interpreted in the light of the following conditions:

(a) The present list of nuclides may be added to from time to time provided the appropriate values of m.p.m.d. are estimated by the same methods used to derive those values currently listed. All such additions are to be subject to prior approval by the external competent authority, in particular the N.S.W. Radiological Advisory Council.

(b) The values of the various parameters used to derive the values of m.p.m.d. (dilution factors, concentration factors, and permissible population exposure levels) may be altered from time to time in the light of more adequate experimental data or changes in accepted international radiological protection standards. All such variations are to be subject to prior approval by the external competent authority, in particular, the N.S.W. Radiological Advisory Council.

(c) If doubts arise at any time as to the interpretation or administration of the formula, they must be resolved by going back to first principles. The principal aim of the authorization is to ensure that the mean annual dose received by individual members of the general public is maintained within acceptable limits, which in the present context are assumed to be those laid down in the Regulations under the New South Wales Radioactive Substances Act of 1957. The ultimate test of the adequacy of the formula is provided by the results of environmental surveys.

(d) Individual monthly discharges may be permitted to exceed the limit defined by the formula provided that the total release over a quarter is within prescribed limits.

(e) The authorization should be critically examined from time to time in the light of the results of environmental surveys.

It should perhaps be re-emphasized that the main purpose of this revision was not, except in the case of tritium, to increase the permissible levels of discharge into the Woronora Estuary, but to produce a rationally-based, self-consistent formula that is sufficiently flexible not to require future modifications in principle, regardless of developments at the Research Establishment. (Numerical values may, of course, require amendment in the light of improved data or changes in recommended permissible exposure levels). Though, in fact the permissible levels of discharge of many nuclides will be increased under the new formulation, there are a number of nuclides which will be subject to more restrictive limits. The present calculations and the results of environmental surveys to date indicate that previous discharge limits have been very conservative.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Fry, R.M. (1964). – Tissue dose from surface deposited β-activity. AAEC/TM273.

Giles, M.S., and Stockdale, J.A.D. (1966). – Results of the Lucas Heights Biological Survey. December 1959 – December 1965. AAEC/E151.

Henriques, F.W. (1952). - Effect of β-rays on the skin as a function of the energy, intensity and duration of radiation. Lab. Investigations. 1. 153.

I.A.E.A. (1963). – Radioactive Waste Disposal into the Sea. STI/PUB/14 Safety Series No. 5 I.A.E.A., Vienna.

ICRP (1955). – Recommendations of the International Commission on Radiological Protection p.16 Supplement No. 6. Brit. J. Rad.

ICRP (1959). – Report of Committee II on Permissible Doses for Internal Radiation. ICRP Publication 2, Pergamon Press.

ICRP (1964). - Recommendations of the Commission, ICRP Publication 6. Pergamon Press.

NAS–NRC (1957). – Effects of Atomic Radiation on Oceanography and Fisheries. NAS–NRC Pub. 551.

NAS-NRC (1959a). – Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters. NAS–NRC Pub. 655.

NAS–NRC (1959b). – Radioactive Waste Disposal from Nuclear–Powered Ships. NAS–NRC Pub. 658.

NAS–NRC (1962). – Disposal of Low–level Radioactive Waste in Pacific Coastal Waters. NAS–NRC Pub. 985.

Nelms, A.T. (1958). – Energy Loss and Range of Electrons and Positrons. NBS Circular 577 (Supplement).

Norwood, W.D. (1963). – Removal of Plutonium and other Transuranic Elements from Man; p.307 of Diagnosis and Treatment of Radioactive Poisoning. I.A.E.A., Vienna.

Todd, J.D. (1961). – Effluent Audit A.A.E.C. internal quarterly reports beginning No. 1 (April – June 1961).

Vinogradov, A.P. (1953). – The Elementary Chemical Composition of Marine Organisms. Memoir II of Sears Foundation for Marine Biology.

Hausckek, E. and Lützen, J. (1964). – Study of the Problems Relating to Radioactive Waste Disposal into the North Sea, II, p.73; O.E.C.D., European Nuclear Energy Agency, Paris.

Ison, A.R.W. (1959). – Safe levels for the discharge of radioactive effluent into the Woronora Estuary. A.A.E.C. internal report K260.

SUMMARY OF EFFLUENT DISCHARGES TO DECEMBER 1965

Date	Report No.	α mCi	Ra-226 mCi	β mCi	Sr-90 mCi	H-3 Ci	Co-58 mCi	Co-60 mCi	Zn-65 mCi	Zr-Nb-95 mCi	Cs-134 mCi	Cs-137 mCi	Ce-141 mCi	U kg	U αmCi	Σβk mCi	β-Σβk mC	
1961																		
April–June	1	0.108	0.034	19.9	3.00			1.5				1.5				9.0	10.9	
July–Sept.	2	0.763	0.046	29.0	9.1			3.8				7.6		1.910	1.298	29.6	−0.6	
Oct.–Dec.	3	0.262	0.057	9.75	3.60			0.0				3.5		0.453	0.308	14.7	−4.9	
Total (9 months)		1.133	0.137	58.7	17.7			5.3				12.6			1.606			
Mean monthly		0.126	0.015	6.52	2.0							1.4			0.268			
1962																		
Jan.–Mar.	4	0.227	0.031	14.0	3.16	2.5		0.0				4.0		0.747	0.508	10.3	3.7	
April–June	5	0.422	0.020*	12.5	1.10	6.5		0.02		0.02		5.8		0.428	0.291	8.0	4.5	
July–Sept.	6	0.221	0.020*	14.84	0.39	3.7		0.0	tr			5.7		0.324	0.220	6.5	8.3	
Oct.–Dec.	7	0.111	0.017*	5.90	0.20	12.0		1.6				0.8		0.112	0.076	2.8	3.2	
Total 1962		0.981	0.088	47.24	4.85	24.7		1.6	tr	tr		16.3			1.095			
Mean monthly		0.082	0.0073	3.94	0.40							1.4			0.091			
1963																		
Jan.–Mar.	8	0.440	0.018*	22.80	5.59	19.3		2.4	~0.4	2.1		17.5		0.456	0.310	33.2	−10.4	
April–June	9	0.284	0.029	18.95	2.19	8.3		2.3	tr	1.8		4.5	~0.3	0.426	0.290	13.3	5.7	
July–Sept.	10	0.550	0.018*	33.80	5.79	1.4		0.9				12.4	0.7	0.09	0.061	25.6	8.2	
Oct.–Dec.	11	0.083*	0.017*	26.20	3.61	17.7		1.8	~0.2		1.1	16.5		0.02	0.014	26.6	−0.4	
Total 1963		1.357	0.082	101.75	17.18	46.7		7.4	~1	3.9	1.1	50.9			0.675			
Mean monthly		0.113	0.0068	8.48	1.43							4.2			0.056			
1964																		
Jan.–Mar.	12	0.091*	0.018*	24.1	3.20	2.3	~2	0.3	~0.2	2.9	tr	7.3	tr	0.69	0.47	17.2	6.9	
April–June	13	0.106	0.029	14.26	1.06	10.9		1.0	3	0.5		1.2		0.51	0.35	4.8	9.5	
July–Sept.	14	0.11*	0.038	16.29	3.00	10.4		0.4		1.0		4.3	0.2	0.045	0.031	11.8	4.5	
Oct.–Dec.	15	0.134	0.035	12.82	3.02	4.0	0.3	0.2		1.0		5.0	0.8	0.036	0.025	13.1	−0.3	
Total 1964		0.441	0.120	67.47	10.28	27.6	~3	1.9	~4	5.4	tr	17.8	~1		0.876			
Mean monthly		0.037	0.010	5.62	0.86	2.3						1.5			0.073			
1965																		
Jan.–Mar.	16	0.25	0.023*	17.50	0.32	5.0		0.2	0.4		1.0			0.07	0.048	3.6	13.9	(a
April–June	17	0.824	0.091	11.58	1.53	14.9		2.2	0.05	0.03	0.1	2.2		0.06	0.041	7.6	4.0	(b
July–Sept.	18	0.370	0.023	15.00	1.30	31.5		0.1	0.2	2.5		2.5		0.034	0.023	7.7	7.3	(c
Oct.–Dec.	19	0.128	0.024	17.54	1.07	50.2		4.3		1.7		2.2		0.015	0.010	10.4	7.1	
Total 1965		**1.572**	**0.161**	61.62	4.22	101.6		6.8	0.7	4.23	1.1	**6.9**			***0.122***			
Mean monthly		**0.131**	**0.013**	5.14	0.35							***0.67***			***0.010***			

TABLE 2

RADIOACTIVITY IN WORONORA SAMPLES – OYSTER FLESH

Period		Mean Activity $\mu\mu$Ci/g Fresh Weight			
		Gross α	Gross β–(K–40)	Sr–90	Zn–65
1961	Woronora	0.08	<1	<0.005	N.D.
	Control	0.06	<1	<0.005	N.D.
1962	Woronora	0.15	<0.3	<0.004	0.07
	Control	0.17	<0.3	<0.003	N.D.
1963	Woronora	0.25	<0.3	<0.004	0.07
	Control	0.36	<0.3	<0.005	N.D.
1964	Woronora	0.23	<0.3	0.002	0.15
	Control	0.20	<0.3	0.002	N.D.
1965	Woronora	0.12	<0.4	0.0008	0.11
	Control	0.33	<0.3	0.0009	N.D.
ximum permissible oncentration		10 +	90 *	1	1000

D. Means not detectable.

Provided Sr–90 is measured separately and that I–126, I–129, I–131, Pb–210, and Ra–224 are not present in significant quantities.

Provided Po–210 and Ra–226 are not present in significant quantities.

$\Sigma\beta_k$ = the contribution of the known β emitters to the gross β count

* = these values are at the lower limit of detection

tr = trace

(a) Plus 2.0 mCi Fe–59 (b) Plus 0.3 mCi Cr–51 (c) Plus 4.0 mCi Be–7

TABLE 3

RADIOACTIVITY IN WORONORA SAMPLES – FISH (MULLET AND BLACKFISH)

Period	Mean Activity $\mu\mu$Ci/g Fresh Weight			
	Gross α	Gross β –(K–40)	Sr–90	Cs–137
1961	0.4	0.3	<0.01	N.D.
1962	0.6	0.2	0.026	N.D.
1963	0.4	0.5	<0.015	0.09
1964	0.14	<0.3	0.01	N.D.
1965	0.46	<0.4		N.D.
Maximum permissible concentration	10 +	90 *	1	200

N.D. Means not detectable.

* Provided Sr–90 is measured separately and that I–126, I–129, I–131, Pb–210, and Ra–224 are not present in significant quantities.

\+ Provided Po–210 and Ra–226 are not present in significant quantities.

TABLE 4

RADIOACTIVITY IN WORONORA SAMPLES – BEACH SAND

Period	Mean Activity $\mu\mu$Ci/g Dry Weight	
	Gross α	Gross β –(K–40)
1961	3.7	2.7
1962	4.3	2.0
1963	3.2	1.3
1964	2.1	0.3
1965	4.9	2.3
Maximum permissible concentration	3000	2500

TABLE 5

THE MAXIMUM PERMISSIBLE ESTUARINE WATER CONCENTRATION AND MAXIMUM PERMISSIBLE MONTHLY DISCHARGES FOR ALL NUCLIDES CONSIDERED BY THE ICRP WITH HALF LIVES GREATER THAN 1 DAY, BASED ON INGESTION OF 70g OF OYSTERS ONLY

Nuclide	$(m.p.d.i.)_{pop}$ μCi (1)	$(mpc)_{oysters}$ $\mu Ci/g$ (2)	Concentration Factor (3)	$(mpc)_{estuary}$ $\mu Ci/ml$	m.p. monthly discharge Ci/month (4)
H-3	2.2	3.1×10^{-2}	1	3.1×10^{-2}	4.3×10^{5}
Be-7	1.5	2.1×10^{-2}	200	1.1×10^{-4}	1400
C-14	0.59	8.3×10^{-3}	3×10^{3}	2.8×10^{-6}	38
Na-22	0.029	4.3×10^{-4}	1	4.3×10^{-4}	5700
P-32	0.015	2.1×10^{-4}	5×10^{4}	4.2×10^{-9}	0.057
S-35	0.044	6.3×10^{-4}	4	1.6×10^{-4}	2100
Cl-36	0.059	8.3×10^{-4}	1	8.3×10^{-4}	1.1×10^{4}
Ca-45	0.0066	9.3×10^{-5}	5	1.9×10^{-5}	260
Ca-47	0.037	5.3×10^{-4}	5	1.1×10^{-4}	1400
Sc-46	0.029	4.3×10^{-4}	10^{3}	4.3×10^{-7}	5.7
Sc-47	0.066	9.3×10^{-4}	10^{3}	9.3×10^{-7}	13
Sc-48	0.022	3.1×10^{-4}	10^{3}	3.1×10^{-7}	4.3
V-48	0.022	3.1×10^{-4}	10^{3}	3.1×10^{-7}	4.3
Cr-51	1.5	1.8×10^{-2}	10^{4}	2.1×10^{-6}	29
Mn-52	0.022	3.1×10^{-4}	10^{4}	3.1×10^{-8}	0.43
Mn-54	0.073	1.0×10^{-3}	10^{4}	1.0×10^{-7}	1.4
Fe-55	0.59	8.3×10^{-3}	6×10^{3}	1.4×10^{-6}	19
Fe-59	0.044	6.3×10^{-4}	6×10^{3}	1.1×10^{-7}	1.4
Co-57	0.37	5.3×10^{-3}	10^{3}	5.3×10^{-6}	72
Co-58	0.073	1.0×10^{-3}	10^{3}	1.0×10^{-6}	14
Co-60	0.037	5.3×10^{-4}	10^{3}	5.3×10^{-7}	7.2
Ni-59	0.15	2.1×10^{-3}	5×10^{2}	4.0×10^{-6}	57
Ni-63	0.022	3.1×10^{-4}	5×10^{2}	6.3×10^{-7}	8.6
Zn-65	0.073	1.0×10^{-3}	1.5×10^{5}	7.0×10^{-9}	0.095
Ge-71	1.5	2.1×10^{-2}	500	4.0×10^{-5}	570
As-73	0.37	5.3×10^{-3}	10^{3}	5.3×10^{-6}	72
As-74	0.037	5.3×10^{-4}	10^{3}	5.3×10^{-7}	7.2
As-76	0.015	2.1×10^{-4}	10^{3}	2.1×10^{-7}	2.9
As-77	0.059	8.3×10^{-4}	10^{3}	8.3×10^{-7}	11
Se-75	0.22	3.1×10^{-3}	10^{2} *	3.1×10^{-5}	430
Br-82	0.22	3.1×10^{-3}	1	3.1×10^{-3}	4.3×10^{4}
Rb-86	0.051	7.3×10^{-4}	10^{2}	7.3×10^{-6}	100
Rb-87	0.073	1.0×10^{-3}	10^{2}	1.0×10^{-5}	140
Sr-85	0.073	1.0×10^{-3}	1	1.0×10^{-3}	1.4×10^{4}
Sr-89	0.0073	1.0×10^{-4}	1	1.0×10^{-4}	1400
Sr-90	0.000073	1.0×10^{-6}	1	1.0×10^{-6}	14
Y-90	0.015	2.1×10^{-4}	10^{3}	2.1×10^{-7}	2.9
Y-91	0.022	3.1×10^{-4}	10^{3}	3.1×10^{-7}	4.3
Zr-93	0.59	8.3×10^{-3}	10^{3}	8.3×10^{-6}	110
Zr-95	0.044	6.3×10^{-4}	10^{3}	6.3×10^{-7}	8.6
Nb-93m	0.29	4.3×10^{-3}	200	2.2×10^{-5}	290
Nb-95	0.073	1.0×10^{-3}	200	5.0×10^{-6}	72
Mo-99	0.15	2.1×10^{-3}	10^{3}	2.1×10^{-6}	29
Tc-96	0.073	1.0×10^{-3}	5×10^{4}	2.1×10^{-8}	0.29
Tc-97m	0.29	4.3×10^{-3}	5×10^{4}	8.7×10^{-8}	1.1
Tc-97	1.5	2.1×10^{-2}	5×10^{4}	4.0×10^{-7}	5.7
Tc-99	0.22	3.1×10^{-3}	5×10^{4}	6.3×10^{-8}	0.86
Ru-97	0.29	4.3×10^{-3}	10^{3}	4.3×10^{-6}	57
Ru-103	0.059	8.3×10^{-4}	10^{3}	8.3×10^{-7}	11

(continued)

TABLE 5 (continued)

Nuclide	$(m.p.d.i.)_{pop}$ μCi (1)	$(mpc)_{oysters}$ μCi/g (2)	Concentration Factor (3)	$(mpc)_{estuary}$ μCi/ml	m.p. monthly discharge Ci/month (4)
106/Rh-106	0.0073	1.0×10^{-4}	10^3	1.0×10^{-7}	1.4
-105	0.073	1.0×10^{-3}	10^3 *	1.0×10^{-6}	14
103	0.22	3.1×10^{-3}	10^3 *	3.1×10^{-6}	43
105	0.073	1.0×10^{-3}	10^3	1.0×10^{-6}	14
-110m	0.022	3.1×10^{-4}	10^3	3.1×10^{-7}	4.3
111	0.029	4.3×10^{-4}	10^3	4.3×10^{-7}	5.7
109	0.15	2.1×10^{-3}	10^4	2.1×10^{-7}	2.9
115m	0.022	3.1×10^{-4}	10^4	3.1×10^{-7}	4.3
115	0.022	3.1×10^{-4}	10^4	3.1×10^{-7}	4.3
114m/In-114	0.015	2.1×10^{-4}	10^5	2.1×10^{-9}	0.029
115	0.066	9.3×10^{-4}	10^5	9.3×10^{-9}	0.13
113	0.066	9.3×10^{-4}	10^3	9.3×10^{-7}	13
122	0.022	3.1×10^{-4}	10^2	3.1×10^{-6}	43
124	0.015	2.1×10^{-4}	10^2	2.1×10^{-6}	29
125	0.073	1.0×10^{-3}	10^2	1.0×10^{-5}	140
125m	0.15	2.1×10^{-3}	10^2	2.1×10^{-5}	290
127m/Te-127	0.044	6.3×10^{-4}	10^2	6.3×10^{-6}	86
129m/Te-129	0.022	3.1×10^{-4}	10^2	3.1×10^{-6}	43
131m	0.044	6.3×10^{-4}	10^2	6.3×10^{-6}	86
-132	0.022	3.1×10^{-4}	10^2	3.1×10^{-6}	43
26	0.0015	2.1×10^{-5}	10^2	2.1×10^{-7}	2.9
29	0.00029	4.3×10^{-6}	10^2	4.3×10^{-8}	0.57
31	0.0015	2.1×10^{-5}	10^2	2.1×10^{-7}	2.9
-131	1.5	2.1×10^{-2}	50	4.0×10^{-4}	5700
-134	0.007	9.3×10^{-5}	50	1.9×10^{-6}	26
-135	0.073	1.0×10^{-3}	50	2.1×10^{-5}	290
-136	0.07	9.3×10^{-4}	50	1.9×10^{-5}	260
-137	0.015	2.1×10^{-4}	50	4.0×10^{-6}	57
-131	0.15	2.1×10^{-3}	500	4.0×10^{-6}	57
-140	0.022	3.1×10^{-4}	500	6.3×10^{-7}	8.6
-140	0.015	2.1×10^{-4}	10^3	2.1×10^{-7}	2.9
-141	0.066	9.7×10^{-4}	10^3	9.7×10^{-7}	13
-143	0.029	4.3×10^{-4}	10^3	4.3×10^{-7}	5.7
-144	0.0073	1.0×10^{-4}	10^3	1.0×10^{-7}	1.3
143	0.037	5.3×10^{-4}	10^3	5.3×10^{-7}	7.2
144	0.05	7.3×10^{-4}	10^3	7.3×10^{-7}	10
-147	0.043	6.3×10^{-4}	10^3	6.3×10^{-7}	8.6
-147	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
-149	0.029	4.3×10^{-4}	10^3	4.3×10^{-7}	5.7
147	0.043	6.3×10^{-4}	10^3	6.3×10^{-7}	8.6
151	0.29	4.3×10^{-3}	10^3	4.3×10^{-6}	57
153	0.06	8.3×10^{-4}	10^3	8.3×10^{-7}	11
152	0.06	8.3×10^{-4}	10^3	8.3×10^{-7}	11
154	0.015	2.1×10^{-4}	10^3	2.1×10^{-7}	2.9
155	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
153	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
-160	0.029	4.3×10^{-4}	10^3	4.3×10^{-7}	5.7
166	0.029	4.3×10^{-4}	10^3	4.3×10^{-7}	5.7
166	0.022	3.1×10^{-4}	10^3	3.1×10^{-7}	4.3
169	0.07	9.3×10^{-4}	10^3	9.3×10^{-7}	13
-170	0.037	5.3×10^{-4}	10^3	5.3×10^{-7}	7.2
-171	0.37	5.3×10^{-3}	10^3	5.3×10^{-6}	72

(continued)

TABLE 5 (continued)

Nuclide	$(m.p.d.i.)_{pop}$ μCi (1)	$(mpc)_{oysters}$ $\mu Ci/g$ (2)	Concentration Factor (3)	$(mpc)_{estuary}$ $\mu Ci/ml$	m.p. monthly discharge Ci/month (4)
Yb-175	0.073	1.0×10^{-3}	10^3	1.0×10^{-6}	13
Lu-177	0.073	1.0×10^{-3}	10^3	1.0×10^{-6}	13
Hf-181	0.05	7.3×10^{-4}	10^3 *	7.3×10^{-7}	10
Ta-182	0.029	4.3×10^{-4}	10^3	4.3×10^{-7}	5.7
W-181	0.29	4.3×10^{-3}	10^5	4.3×10^{-8}	0.57
W-185	0.073	1.0×10^{-3}	10^5	1.0×10^{-8}	0.14
W-187	0.05	7.3×10^{-4}	10^5	7.3×10^{-8}	1.0
Re-183	0.43	6.3×10^{-2}	10^3 *	6.3×10^{-6}	86
Re-186	0.07	9.3×10^{-4}	10^3	9.3×10^{-7}	13
Re-187	2.2	3.1×10^{-2}	10^3	3.1×10^{-5}	430
Os-185	0.05	7.3×10^{-4}	10^3 *	7.3×10^{-7}	10
Os-191	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
Os-193	0.043	6.3×10^{-4}	10^3	6.3×10^{-7}	8.6
Ir-192	0.029	4.3×10^{-4}	10^3 *	4.3×10^{-7}	5.7
Pt-191	0.073	1.0×10^{-3}	10^3 *	1.0×10^{-6}	14
Pt-193m	0.73	1.0×10^{-2}	10^3	1.0×10^{-5}	140
Pt-193	0.7	9.3×10^{-3}	10^3	9.3×10^{-6}	130
Au-196	0.15	2.1×10^{-3}	300	7.0×10^{-6}	95
Au-198	0.37	5.3×10^{-4}	300	1.8×10^{-6}	24
Au-199	0.15	2.1×10^{-3}	300	7.0×10^{-6}	95
Hg-197m	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
Hg-197	0.22	3.1×10^{-3}	10^3	3.1×10^{-6}	43
Hg-203	0.015	2.1×10^{-4}	10^3	2.1×10^{-7}	2.9
Tl-200	0.29	4.3×10^{-3}	10^4 *	4.3×10^{-7}	5.7
Tl-201	0.22	3.1×10^{-3}	10^4	3.1×10^{-7}	4.3
Tl-202	0.073	1.0×10^{-3}	10^4	1.0×10^{-7}	1.4
Tl-204	0.073	1.0×10^{-3}	10^4	1.0×10^{-7}	1.4
Pb-203	0.29	4.3×10^{-3}	50	8.7×10^{-5}	1100
Pb-210	0.73×10^{-4}	1.0×10^{-6}	50	2.1×10^{-8}	0.29
Bi-206	0.029	4.3×10^{-4}	50	8.7×10^{-6}	110
Bi-207	0.043	6.3×10^{-4}	50	1.3×10^{-5}	170
Bi-210	0.029	4.3×10^{-4}	50	8.7×10^{-6}	110
Po-210	0.5×10^{-3}	7.3×10^{-6}	10^4	7.3×10^{-10}	0.010
Ra-223	0.5×10^{-3}	7.3×10^{-6}	50	1.5×10^{-7}	2.0
Ra-224	1.5×10^{-3}	2.1×10^{-5}	50	4.0×10^{-7}	5.7
Ra-226	0.73×10^{-5}	1.0×10^{-7}	50	2.1×10^{-9}	0.029
Ra-228	2.2×10^{-5}	3.1×10^{-7}	50	6.3×10^{-9}	0.086
Ac-227	1.5×10^{-3}	2.1×10^{-5}	10^3 *	2.1×10^{-8}	0.29
Th-227	0.015	2.1×10^{-4}	10^3	2.1×10^{-7}	2.9
Th-228	0.005	7.3×10^{-5}	10^3	7.3×10^{-8}	1.0
Th-230	1.5×10^{-3}	2.1×10^{-5}	10^3	2.1×10^{-8}	0.29
Th-231	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
Th-232	1.5×10^{-3}	2.1×10^{-5}	10^3	2.1×10^{-8}	0.29
Th-234	0.015	2.1×10^{-4}	10^3	2.1×10^{-7}	2.9
Th natural	0.73×10^{-3}	1.0×10^{-5}	10^3	1.0×10^{-8}	0.14
Pa-230	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
Pa-231	0.7×10^{-3}	9.3×10^{-6}	10^3	9.3×10^{-9}	0.13
Pa-233	0.073	1.0×10^{-3}	10^3	1.0×10^{-6}	14
U-230	3.7×10^{-3}	5.2×10^{-5}	10	5.2×10^{-6}	72
U-233	0.022	3.1×10^{-4}	10	3.1×10^{-5}	430
U-234	0.022	3.1×10^{-4}	10	3.1×10^{-5}	430

(continued)

TABLE 5 (continued)

Nuclide	$(m.p.d.i.)_{pop}$ μCi (1)	$(mpc)_{oysters}$ $\mu Ci/g$ (2)	Concentration Factor (3)	$(mpc)_{estuary}$ $\mu Ci/ml$	m.p. monthly discharge Ci/month (4)
-235	0.022	3.1×10^{-4}	10	3.1×10^{-5}	430
-238	0.029	4.3×10^{-4}	10	4.3×10^{-5}	570
-natural	0.015	2.1×10^{-4}	10	2.1×10^{-5}	290
-237	2.2×10^{-3}	3.1×10^{-5}	10^3	3.1×10^{-8}	0.43
-239	0.73	1.0×10^{-3}	10^3	1.0×10^{-6}	14
-238	0.0037	5.3×10^{-5}	10^3	5.3×10^{-8}	0.72
-239	0.0037	5.3×10^{-5}	10^3	5.3×10^{-8}	0.72
-241	0.15	2.1×10^{-3}	10^3	2.1×10^{-6}	29
-242	0.0037	5.3×10^{-5}	10^3	5.3×10^{-8}	0.72
-241	2.9×10^{-3}	4.3×10^{-5}	10^3	4.3×10^{-8}	0.57
-243	2.9×10^{-3}	4.3×10^{-5}	10^3	4.3×10^{-8}	0.57
-242	0.015	2.1×10^{-4}	10^3	2.1×10^{-7}	2.9
-243	0.0037	5.3×10^{-5}	10^3	5.3×10^{-8}	0.72
-244	0.005	7.3×10^{-5}	10^3	7.3×10^{-8}	1.0
-245	2.9×10^{-3}	4.3×10^{-5}	10^3	4.3×10^{-8}	0.57
-246	2.9×10^{-3}	4.3×10^{-5}	10^3	4.3×10^{-8}	0.57
-249	0.43	6.3×10^{-3}	10^3 *	6.3×10^{-6}	86
-249	2.9×10^{-3}	4.3×10^{-5}	10^3 *	4.3×10^{-8}	0.57
-250	0.0073	1.0×10^{-4}	10^3	1.0×10^{-7}	1.4
-252	0.005	7.3×10^{-5}	10^3	7.3×10^{-8}	1.0

tes to Table 5

) Maximum permissible daily intake for a member of the general public based on a liquid intake of 2.2 l/day at a concentration equal to 1/30 of the 168 hr maximum permissible water concentration listed in the 1959 I.C.R.P. recommendations.

) Maximum permissible concentration in oysters assuming a daily intake of 70 g.

) Ratio of concentration of element in oyster flesh to that in the water, at equilibrium. The values have been derived from numerous sources. Asterisked values (*) have been estimated by comparison with metabolically similar elements.

) Maximum permissible monthly discharge based on a dilution factor of 10^3 and a release of 3×10^6 gallons of effluent per month from site; that is an effective dilution volume of 3×10^9 gallons = 1.4×10^{13} ml.

TABLE 6

MAXIMUM PERMISSIBLE MONTHLY DISCHARGE OF INDIVIDUAL NUCLIDES LISTED ACCORDING TO ATOMIC MASS CONSIDERING BOTH INTERNAL AND EXTERNAL RADIATION EXPOSURE PATHWAYS AND LIMITED TO A MAXIMUM OF 1000 Ci FOR TRITIUM AND 100 Ci FOR ALL OTHER NUCLIDES

Nuclide	m.p.m.d. Ci/month
H-3	1000
Be-7	100
C-14	38
Na-22	8.3
P-32	0.057
S-35	100
Cl-36	5.0
Ca-45	100
Ca-47	3.8
Sc-46	5.7
Sc-47	13
Sc-48	4.3
V-48	4.3
Cr-51	14
Mn-52	0.28
Mn-54	1.1
Fe-55	19
Fe-59	0.8
Co-57	31
Co-58	5.1
Co-60	2.1
Ni-59	57
Ni-63	8.6
Zn-65	0.095
Ge-71	100
As-73	72
As-74	5.7
As-76	2.9
As-77	11
Se-75	100
Br-82	11
Rb-86	1.6
Rb-87	100
Sr-85	100
Sr-89	2.0
Sr-90	1.2
Y-90	1.2
Y-91	2.0
Zr-93	100
Zr-95	8.6
Nb-93m	100
Nb-95	72
Mo-99	29
Tc-96	0.29
Tc-97m	1.1
Tc-97	5.7
Tc-99	0.86
Ru-97	57
Ru-103	11
Ru-106/Rh-106	1.4
Rh-105	14
Pd-103	43

Nuclide	m.p.m.d. Ci/month
Ag-105	14
Ag-110m	4.3
Ag-111	3.5
Cd-109	2.9
Cd-115m	1.4
Cd-115	1.4
In-114m/In-114	0.029
In-115	0.13
Sn-113	13
Sb-122	2.3
Sb-124	29
Sb-125	100
Te-125m	100
Te-127m/Te-127	5.7
Te-129m/Te-129	2.1
Te-131m	86
Te-132	43
I-126	2.9
I-129	0.57
I-131	2.9
Cs-131	100
Cs-134	26
Cs-135	100
Cs-136	19
Cs-137	2.8
Ba-131	57
Ba-140	1.8
La-140	2.5
Ce-141	1.8
Ce-143	3.1
Ce-144	1.3
Pr-143	4.1
Nd-144	1.5
Nd-147	3.4
Pm-147	29
Pm-149	3.5
Sm-147	1.5
Sm-151	57
Sm-153	11
Eu-152	11
Eu-154	2.9
Eu-155	29
Gd-153	29
Tb-160	5.7
Dy-166	5.7
Ho-166	2.0
Er-169	13
Tm-170	4.1
Tm-171	72
Yb-175	13
Lu-177	13
Hf-181	10

Nuclide	m.p.m.d. Ci/month
Ta-182	5.7
W-181	0.57
W-185	0.14
W-187	0.32
Re-183	86
Re-186	13
Re-187	100
Os-185	10
Os-191	29
Os-193	4.1
Ir-192	5.7
Pt-191	14
Pt-193m	100
Pt-193	100
Au-196	95
Au-198	24
Au-199	95
Hg-197m	29
Hg-197	43
Hg-203	2.9
Tl-200	5.7
Tl-201	4.3
Tl-202	1.4
Tl-204	1.4
Pb-203	100
Pb-210	0.29
Bi-206	100
Bi-207	100
Bi-210	100
Po-210	0.010
Ra-223	1.5
Ra-224	1.5
Ra-226	0.029
Ra-228	0.086
Ac-227	0.29
Th-227	1.5
Th-228	1.0
Th-230	0.29
Th-231	1.5
Th-232	0.29
Th-234	2.9
Th-natural	0.14
Pa-230	29
Pa-231	0.13
Pa-233	14
U-230	1.5
U-233	1.5
U-234	1.5
U-235	1.5
U-236	1.5
U-238	1.5
U-natural	1.5

(continued)

TABLE 6 (continued)

Nuclide	m.p.m.d. Ci/month
Np-237	0.43
Np-239	14
Pu-238	0.72
Pu-239	0.72
Pu-241	1.5
Pu-242	0.72
Am-241	0.57
Am-243	0.57
Cm-242	1.5
Cm-243	0.72
Cm-244	1.0
Cm-245	0.57
Cm-246	0.57
Bk-249	1.5
Cf-249	0.57
Cf-250	1.4
Cf-252	1.0

TABLE 7

NUCLIDES LISTED IN ORDER OF THEIR MAXIMUM PERMISSIBLE MONTHLY DISCHARGES CONSIDERING BOTH INTERNAL AND EXTERNAL RADIATION EXPOSURE PATHWAYS AND LIMITED TO A MAXIMUM OF 1000 Ci FOR TRITIUM AND 100 Ci FOR ALL OTHER NUCLIDES

m.p.m.d.	Nuclide			
< 0.1 Ci	Po-210(.010) Ra-226(.029) In-114m-114(.029) P-32(.057) Ra-228(.086) Zn-65(.09			
0.1 Ci-1 Ci	In-115(.13)	Pa-231(.13)	W-185(.14)	Th nat(.14)
	Mn-52(.28)	Tc-96(.29)	Pb-210(.29)	Ac-227(.29)
	Th-230,232(.29)	W-187(.32)	Np-237(.43)	I-129(.57)
	W-181(.57)	Am-241,243(.57)	Cm-245,246(.57)	Cf-249(.57)
	Pu-238,239,242(.72)	Cm-243(.72)	Fe-59(.80)	Tc-99(.86)
1 Ci - 10 Ci	Th-228(1.0)	Cm-244(1.0)	Cf-252(1.0)	Mn-54(1.1)
	Tc-97m(1.1)	Sr-90(1.2)	Y-90(1.2)	Ce-144(1.3)
	Ru-106(1.4)	Cd-115m,115(1.4)	Tl-202,204(1.4)	Cf-250(1.4)
	Ra-223,224(1.5)	Pu-241(1.5)	"Other α"(1.5)	Rb-86(1.6)
	Ba-140(1.8)	Ce-141(1.8)	Sr-89(2.0)	Y-91(2.0)
	Ho-166(2.0)	Co-60(2.1)	Te-129m-129(2.1)	Sb-122(2.3)
	La-140(2.5)	Cs-137(2.8)	As-76(2.9)	Cd-109(2.9)
	I-126,131(2.9)	Eu-154(2.9)	Hg-203(2.9)	Th-234(2.9)
	Ce-143(3.1)	Nd-147(3.4)	Ag-111(3.5)	Pm-149(3.5)
	Ca-47(3.8)	Pr-143(4.1)	Tm-170(4.1)	Os-193(4.1)
	Sc-48(4.3)	V-48(4.3)	Ag-110m(4.3)	Tl-201(4.3)
	Cl-36(5.0)	Co-58(5.1)	Sc-46(5.7)	As-74(5.7)
	Tc-97(5.7)	Te-127m-127(5.7)	Tb-160(5.7)	Dy-166(5.7)
	Ta-182(5.7)	Ir-192(5.7)	Tl-200(5.7)	Na-22(8.3)
	Ni-63(8.6)	Zr-95(8.6)		
10 Ci - 100 Ci	Hf-181(10)	Os-185(10)	As-77(11)	Br-82(11)
	Ru-103(11)	Sm-153(11)	Eu-152(11)	Sc-47(13)
	Sn-113(13)	Er-169(13)	Re-186(13)	Yb-175(13)
	Lu-177(13)	Cr-51(14)	Rh-105(14)	Ag-105(14)
	Pt-191(14)	Pa-233(14)	Np-239(14)	Fe-55(19)
	Cs-136(19)	Au-198(24)	Cs-134(26)	Mo-99(29)
	Sb-124(29)	Pm-147(29)	Eu-155(29)	Gd-153(29)
	Os-191(29)	Hg-197(29)	Pa-230(29)	Co-57(31)
	C-14(38)	Pd-103(43)	Te-132(43)	Hg-197(43)
	Ni-59(57)	Ru-97(57)	Ba-131(57)	Sm-151(57)
	Nb-95(72)	As-73(72)	Tm-171(72)	Te-131m(86)
	Re-183(86)	Au-196,199(95)		
100 Ci	Be-7 S-35 Ca-45 Se-75 Ge-71 Sr-85 Rb-87 Nb-93m Zr-93 Sb-125 Te-125m Cs-131,135 Re-187 Pt-193,193m Pb-203 Bi-206,207,210			
1000 Ci	H-3			