SAFETY SERIES

No. 10

Disposal of Radioactive Wastes into Fresh Water

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA 1963

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REPORT OF AN AD HOC PANEL OF EXPERTS

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FOREWORD

One of the important tasks of the International Atomic Energy Agency is to encourage the development of safe and practical methods for managing radioactive wastes. In carrying out this task the Agency has used the experience and talents of highly qualified experts from many disciplines and from widely distributed parts of the world.

This report is the work of an ad hoc panel of experts convened by the Agency to study the disposal of radioactive wastes into fresh water. It met on three occasions, the final meeting being held in October 1961. In view of the fact that a previous ad hoc panel of experts studied radioactive waste disposal into the sea and reported its findings in February 1960, this report completes the initial phase of the Agency's work relative to the discharge of radioactive wastes into the hydrosphere. It presents the opinions of the panel members and not necessarily those of their Governments or of the International Atomic Energy Agency.

SIGVARD EKLUND
Director General

March 1963

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PART I

I. INTRODUCTION

A. IMPORTANCE OF FRESH WATERS

Fresh water is a basic necessity of man. It is essential for most forms of life and for the maintenance and growth of civilization.

Fresh water has manifold uses which may be broadly classified as domestic, industrial and recreational uses. Domestic use includes drinking, cooking and cleansing; industrial requirements cover applications in many processes such as those in the chemical, photographic, textile and other manufacturing industries, in power production and transport, as well as for uses in agriculture and horticulture. Also included here should be water bodies which support commercial fisheries. Recreational uses involve such activities as swimming, sailing and sport fishing.

The amount of water required for these purposes is already great and is growing rapidly as the world population increases and as its agricultural and industrial needs expand. In many areas of the world fresh water is already in short supply and the demand for it is increasing. One example should suffice to illustrate the heavy use of water in developed countries. At present the average urban use of water for domestic purposes in the United States is greater than 500 l/d per person; its use increases to over 4000 l/d per person if the water required for industrial purposes is included. This already heavy consumption is predicted to double by 1975.

Because of its important role in man's present and future economy the protection of this natural resource is an important task.

B. CHARACTER OF FRESH WATERS

The world's supplies of fresh water are maintained predominantly by rain and snow. The continuous cycle of evaporation and precipitation which supports this has many variations, as illustrated in Fig. 1. Nevertheless, almost all natural moisture, in whatever form - in the atmosphere, on the surface of the earth or underground - forms part of a world-wide circulatory system.

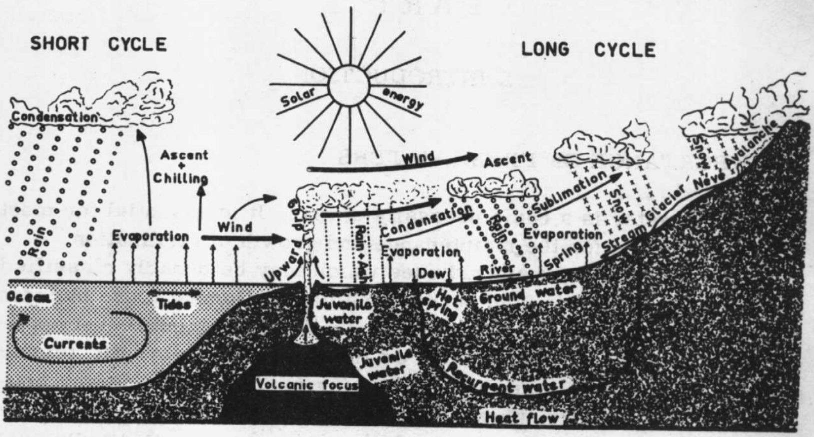

Fig.1

Principal aspects of the cycle of terrestrial water
(KUENEN, P.H., Realms of water, Cleaver-Hume Press, London (1955))

The distinction between surface water and ground water is based merely on their temporary positions relative to the land surface. The two are closely interrelated parts of a larger system of circulating waters. In humid climates, ground waters generally flow into and support the discharge of streams and springs or may flow directly into the sea; in arid climates surface streams generally seep down into the ground and support the flow of ground water. The movement of ground water may be divided into two interrelated zones: the non-saturated zone (also called the vadose zone of aeration) and the saturated zone. The non-saturated zone exists between the land surface and the upper surface of the saturated zone (i.e. the water-table). In this zone pore spaces are filled partly with water and water vapour and partly with air; the movement of water is essentially vertical, usually downward, but under certain conditions may be temporarily upward. The thickness of the non-saturated zone may range from nearly zero in humid climates where the terrain is flat, to several hundreds of meters in arid or semi-arid climates. In the saturated zone, on the other hand, all pore spaces are completely filled with water and the flow is essentially horizontal except near areas of discharge into streams or wells and near ground-water divides.

In addition to supplying domestic and industrial water, fresh-water bodies also constitute storage, transport and dispersion systems which civilized man has utilized to flush away the wastes of cities and industries. This latter use of water systems has considerable economic importance and is a significant, if not always obvious, factor in the development of industries requiring convenient and economical disposal of wastes.

The protection of the multiple use of bodies of water becomes increasingly difficult as the volumes and complexity of domestic and industrial wastes increase and it cannot be effective in the absence of detailed knowledge of the effects of these wastes.

C. NATURE AND SOURCES OF RADIOACTIVE WASTES

Some of the newest and most complex wastes are produced by the nuclear energy industry. When an atom undergoes fission and releases energy, or when certain atoms are bombarded by neutrons, the resulting materials emit ionizing radiations which can damage living organisms. The radioactivity of these materials decreases only with time and their radioactive properties cannot be altered or destroyed by any physical, chemical or biological treatment. In this respect, radioactive wastes differ from all other types of wastes.

It must be noted, of course, that even under natural conditions most bodies of water contain trace amounts of radioisotopes that are derived primarily from radioactive rocks and minerals with which the water has been in contact and which contribute to the natural or background radiation to which man is universally exposed.

Artificially produced radioactive materials are used in many ways and in many places, but, depending on the degree of containment necessary for safe handling, the wastes which result from their use may be divided into three general categories; high-, intermediate- and low-activity level, as shown diagrammatically by Fig. 2. High-activity waste, representing the preponderance of waste produced by the nuclear energy industry, is not purposely released to the environment and must be immobilized and stored for indefinite

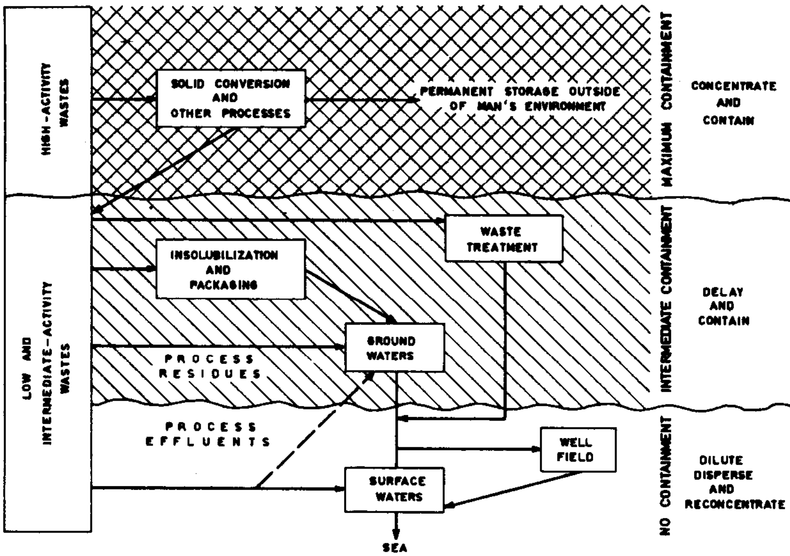

Fig. 2

Required containment of radioactive wastes

periods. Therefore this type of waste will accordingly not be considered further in this report, except to point out that the processing of such waste usually involves the production of quantities of wastes having much lower levels of radioactivity, in the range of a few to several thousand picocuries per liter, as a kind of by-product. Thus the percentage of the total radioactive waste which is being released to the environment is very small indeed.

Proper management of radioactive waste requires the consideration of two basic features: safety and economy. It is generally agreed that the release of radioactive waste should be restricted as far as possible in order to keep the radiation exposures at a minimum.

The handling and disposal of radioactive waste from a plant requires many difficult administrative and engineering decisions. Absolute decontamination of a plant effluent may not be possible. Suitable decontamination of some higher-activity-level wastes may be attained by the use of existing methods only at a cost so great that, in some cases, the benefits of the plant may be nullified. On the other hand, a minimal purification system which adds little or no economic burden to the project may not be in the best long-range interest of the public. Between these two extremes lies a rational compromise whereby some small exposure increment is acceptable so that the benefits of the project may be obtained without a substantial penalty in cost.

D. PURPOSE AND SCOPE OF REPORT

The purpose of this report is to present the principles and practices of radioactive waste management which will ensure that the use of fresh-water systems will in no way be jeopardized. Major attention has been devoted to disposal in streams, lakes and subsurface waters. The report does not include specific studies of other environments, such as estuaries, glaciers and icecaps, snow, etc. Much of the information concerning fresh waters applies to estuaries as well, even though it should be recognized that estuarine and fresh-water environments differ in many important respects.

The main body of the report is a general treatise on the fate of radioactive wastes disposed into fresh-water systems; radiation exposure estimation and control; site and monitoring requirements; and the legal, administrative and organizational principles of radioactive-waste pollution control at national and international levels. Conclusions and recommendations are presented. Factors of particular significance are treated in Part II in more detail than is possible in the main body of the report. Subjects on which considerable research is currently being undertaken, such as radioecology, are treated more fully than those, such as hydrology, for which a number of excellent textbooks already exist.

II. FATE OF RADIOACTIVE WASTES INTRODUCED INTO FRESH WATER

If a radioactive waste is introduced into a body of water, various natural processes begin to dilute, disperse, deposit, remove, transform and reconcentrate all or part of the radioactive materials involved. An understanding of these processes is required for an accurate estimation of the movement and fate of the radionuclides in a water system and, similarly, for an accurate estimation of the degree of hazard involved.

The important factors are the movement of the water, the dispersal of the dissolved and suspended matter in the water, the adsorption of substances by natural materials in contact with the water and incorporation into the biota.

A. STREAMING, TURBULENCE AND ISOTOPIC DILUTION

When a waste is introduced into flowing water, such as a river, it is dispersed by molecular diffusion, by dispersion resulting from the method of discharge, e.g. a submerged jet, and by turbulent diffusion, In almost all cases turbulent dispersion is by far the most important dilution mechanism. In addition, when a radioisotope is first introduced into a body of water it will be isotopically diluted with the stable form of the same element which is already present in the water in a dissolved state. It will also become isotopically diluted by exchange with the stable form of the element which is not in solution. In fast-flowing turbulent streams dispersion takes place much more rapidly than in turgid streams and in lakes and ground waters dilution can be a slow process.

Dilution must be considered as a function of both time and distance. It is possible, for example, that in a given stream the dilution that obtains a fixed distance downstream from a point of waste injection will be greater when the stream is flowing at a low velocity than when flowing at a high velocity, Generally speaking, dilution as a function of distance from a point of waste injection is more important than dilution as a function of time.

The minimum dilution for different flow conditions can be estimated from a study of velocity profiles downstream from the place of discharge. Useful information can be obtained from models which simulate the actual flow conditions, and from studies (in situ) with fluorescein and other tracers. Dispersion of wastes introduced into a fresh-water system may be reduced by stratification or laminar flow.

Where wastes are discharged into a section of a stream affected by tides some field investigations are usually necessary. If the discharge is fairly continuous, the mean dilution and dispersion characteristics are of primary interest. If intermittent discharge is possible, a knowledge of the stages of the tide which are most favourable for dispersion of the waste is desired. In preparation for coping with accidental releases of large quantities of radioactive materials, the probable dilution and dispersion patterns at various stages of the tide should be determined.

B. SEDIMENTATION, ION-EXCHANGE AND ADSORPTION

Any solid particles discharged into fresh water or formed later in the water (see section C) will be affected by water movements. Particles which are more dense than the water will tend to settle out, deposition increasing as stream turbulence decreases. The largest and heaviest particles will of course settle out first.

Some fraction of the radionuclides released into fresh-water environments becomes associated with suspended materials and bottom sediments through ion-exchange and adsorption processes. The natural materials responsible for much of the retention capacity of water-borne sediments are the clay minerals and humic substances. The tenacity with which the radionuclides are retained varies according to the chemical properties of the radionuclides, the materials with which they are associated and the nature of the receiving waters. A change in the chemical composition or physical state of a water body may result in the liberation of radioactive materials from suspended particles and sediments.

The removal of radioactive materials from the water by precipitation and sedimentation will reduce exposure which would otherwise result from the use of the water. It has to be remembered, however, that sediments may be redistributed at times of high river flow, or exposed during low-water conditions. In addition, many forms of aquatic life are closely associated with bottom sediments.

As a result of differential adsorption, certain radionuclides are concentrated in sediments much more easily than others.

C. CO-PRECIPITATION AND FLOCCULATION

Radioactive wastes are chemical mixtures. Upon discharge the wastes can enter into chemical reactions with the receiving water. As a result of such reactions, precipitates containing radionuclides may form and settle out. Where receiving waters come into contact with other waters of a different chemical composition, particularly in estuaries and at river junctions, new chemical reactions leading to precipitation or re-solution of already precipitated materials may occur.

The likelihood of precipitation reactions between different kinds of wastes and various receiving waters can, to a large extent, be investigated in the laboratory.

D. UPTAKE BY AQUATIC ORGANISMS

The tissues of plants and animals contain many of the elements present in their external environment and when certain radionuclides are introduced into aquatic environments they may be taken up by the organisms living in that environment. The amount of accumulation will vary over many orders of magnitude depending upon the element involved and various physical, chemical and biological factors. In the case of elements essential to life, such as nitrogen, phosphorus, iodine, potassium, calcium, carbon, magnesium, manganese, iron, copper, zinc, boron and sulphur, they are present in much higher concentrations in the organisms than in the environment and are assimilated by the organisms much more readily than other elements not commonly found in the biota. The radioisotopes of a few uncommon elements, such as caesium and strontium, may also spread out in the biota, however, because they follow metabolic pathways similar to those of essential elements of the same chemical group to which they belong.

The radionuclides will be taken up by the organism through the processes of:

(a) Adsorption (concentration on the exposed surfaces); and
(b) Incorporation (uptake by the organism directly from the water or from food).

The relative importance of these processes will depend upon the kind and quantity of organisms involved, the nature and concentration of the radioisotope available and its physical and chemical state and the presence of other substances dissolved in the water. Particularly important to the total uptake of an element is the presence of other elements of similar metabolic behaviour.

Radioisotopes can be very usefully applied in determining the relative concentration of elements taken up by aquatic organisms. The "concentration factor" $[\frac{\mu c/g \text{ of organism}}{\mu c/ml \text{ of water}}]$ for any radionuclide cannot exceed the ratio which exists between the concentrations of the stable form of the element in the organism and in the water. Maximum concentration factors for various radionuclides can thus be predicted from conventional quantitative chemical measurements. Such predictions will usually be high, however, because the quantity of the element available for exchange from the solids of the ecosystem is not taken into account. For short-lived radionuclides accumulated by fish, significant radioactive decay can occur if the introduced nuclide must reach the fish via a long food chain. In addition, several days or weeks may be required for the nuclide to become uniformly mixed with stable atoms of the same element present in the organs of deposition. Seasonal changes can also be of significance since the rate at which elements are replaced in the organisms is dependent upon metabolic rates.

E. SPECIAL FEATURES OF LAKE ENVIRONMENTS

The foregoing considerations apply, in general, to all water environments, whether flowing or still. There are, however, some features peculiar to lake environments which are of importance. During warm seasons heat is radiated into lakes from above and is absorbed into the uppermost layers. These layers are ploughed under by the wind and distributed by turbulent currents within an upper layer which is usually only a few meters deep (Fig. 3(a)). This upper layer (epilimnion) is, through being warmed, lighter than the deeper cold water and does not mix freely with it. Sufficient light in the upper warm layer allows production of organic substances by photosynthesis in plants. Therefore radionuclides are incorporated into aquatic organisms mainly in this layer.

Dead organisms and other suspended organic materials sink out of the upper layer into the zone lying below it (the transition zone or metalimnion) and are here partly decomposed. The oxygen content of this layer is thereby diminished (Fig. 3(a)). Under these conditions, radionuclides which have been bound in the organisms may be released.

Organic substances which do not decompose in the transition zone sink deeper and, according to the depth of the lake, decompose mainly in deeper water layers (hypolimnion) or on the lake bed. The radionuclides contained in the dead organisms are liberated to the water by autolysis and microbial action and may be adsorbed by sediment or become incorporated into other organisms. The decomposition of the organic substances depletes the available oxygen. If the oxygen is completely consumed during stagnation, the solubility and adsorption characteristics of many substances in the sediment may change. This occurs chiefly in fairly shallow lakes or in those burdened with organic wastes.