ANNEX F

ENVIRONMENTAL CONTAMINATION *(continued)*

PART IV

Disposal of radio-active wastes and releases from accidents in nuclear reactors

CONTENTS

I. Disposal of radio-active wastes

INTRODUCTION

1. The problems of waste disposal have arisen with civilization and have become increasingly complex with its development. The use of atomic energy has increased the already complicated problems of disposing of the wastes arising from human communities. Radio-active materials could be transmuted into non-radio-active materials by further neutron capture, but this procedure would not be economic. Chemical treatment merely transfers wastes to a more convenient form while leaving a lower concentration of radio-activity in the treated wastes. With the continuing extension of isotope technology in industry and medicine and the development of nuclear power, there will be larger quantities of radio-activity to be stored and there will also be an increase in the amount of low activity wastes released into man's environment. It will therefore become more and more important to control these releases and to assess the contribution they make to man's exposure to radiation.

CLASSIFICATION OF RADIO-ACTIVE WASTES

2. According to their physical state, radio-active wastes are classified as solid, liquid and gaseous. Though no fixed classification system has been agreed upon, liquid wastes can be arbitrarily divided into three groups according to their specific activity: low-, intermediate- and high-level wastes.[1-4] These terms are used to describe the approximate concentration of activity in the particular waste materials and their quantitative definition varies from one establishment to another. Low-level wastes are those having a range of activity from a trace amount up to one microcurie per litre; intermediate-level wastes have concentration up to three curies per litre; and high-level wastes have specific activities up to hundreds of curies per litre.[1]

METHODS OF DISPOSAL

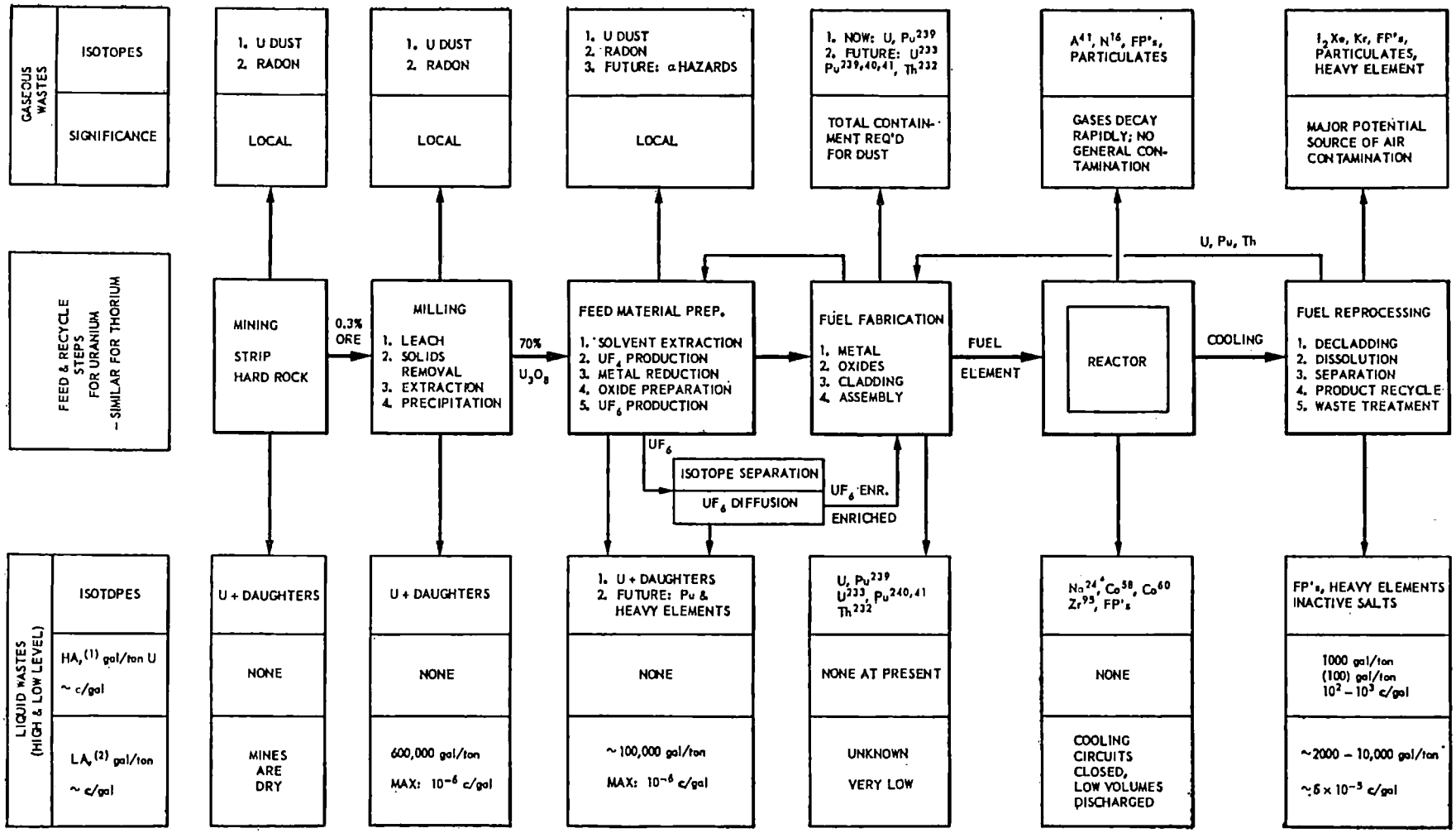
3. Methods of waste disposal must aim at reducing, as far as practicable, the radiation dose to man. Two basic methods are available to achieve this aim. The first is to contain the waste in shielded areas and to absorb most of the radiation in the shield. If special attention is paid to the problems of siting, containment and shielding, any quantity of radio-activity can be dealt with in this way. The second method is to disperse the radio-activity in the environment so that most of the radiation energy is absorbed by the diluting material, and again the radiation dose to man can be kept low. There is, however, a limit to the capacity of the environment to accept wastes without causing excessive radiation dose to man. Broadly speaking, therefore, the first method is the appropriate one for high-level wastes, and the second is satisfactory for low-level wastes. Intermediate-level wastes must be considered on their merits and are usually partly contained and partly dispersed.

ORIGIN AND NATURE OF RADIO-ACTIVE WASTES[5-15]

4. Radio-isotopes originate from three different sources: natural radio-active isotopes with their decay products, fission products and radio-isotopes obtained as a result of activation. By far the greatest quantity of radio-activity in the form of wastes produced at the present time originates from the reactor-fuel cycle. A general flow-sheet indicating the types of waste produced during the nuclear fuel cycle complex is given in figure 1.[7] Smaller amounts of radio-activity occur in the wastes from medical and industrial uses of isotopes. Although these releases are small, they take place in a very large number of establishments and the disposal problems thus posed are by no means negligible.

GASEOUS AND AIRBORNE WASTES

5. Gaseous and airborne radio-active wastes are produced during feed material production, isotope separation, fuel element fabrication, fuel reprocessing and reactor operation. During the re-processing of shortly-cooled fuel elements, fission product gases are released,



(1) HIGH ACTIVITY WASTE: ACTIVITY IS ORDER OF MAGNITUDE ESTIMATE, CURIES/GAL
(2) LOW ACTIVITY WASTE;

Figure 1. Schematic flowsheet for origin of wastes

including Kr^{85}, Xe^{133} and I^{131}. Where air is used as a coolant for reactor cores or shields, the short-lived isotope A^{41} appears in large quantities. C^{14} may be produced in a reactor by irradiation of the graphite moderator, or of the carbon dioxide used as a coolant, and by irradiation of nitrogen.

6. Before being discharged into the atmosphere, airborne and gaseous wastes may have to be partly decontaminated through various devices.[16] Isotopes of the noble gases are diluted by meteorological processes and the dose to man can be adequately controlled by the selection of a suitable stack height. Kr^{85} may in the future give rise to significant exposures if improved methods of treating gaseous effluents are not developed. Other materials, notably isotopes of iodine, are deposited from the air and may be substantially reconcentrated by agricultural processes. This introduction of radio-activity into the food chain is usually likely to contribute more to the radiation dose to man than direct exposure to the airborne waste.

7. Quantitative information on the amounts of radio-activity discharged in gaseous wastes is extremely sparse, but both the United Kingdom and the United States have published some information relating to atomic energy installations. Some of these data are summarized in table I.[17] Because of the various ways in which gaseous discharges can cause radiation exposure to man, the discharge figures in table I cannot be used directly to assess the environmental consequences of the discharges. However, in many cases, detailed assessments have been made of the resultant radiation doses to man and it has been found that these are very small.[18] It is reasonably certain that gaseous wastes from all sources make a very small contribution to man's total radiation dose.

High-level radio-active liquid wastes

8. Wastes of high activity must be stored for long periods of time so as to prevent their release into the environment. At present, all high-level activity wastes from the re-processing of reactor fuel are kept in a concentrated liquid state in tanks. These tanks are either placed in buildings above ground or, more commonly, underground.

9. Despite a number of shortcomings, such as self-heating, radiolysis and corrosion with leakage as a possible consequence, storage of liquid high-level activity wastes in tanks can be considered as satisfactory. Nevertheless, research is being carried out to make possible the storage and disposal of high-level activity wastes in the solid state, as this will provide their safe fixation for a long period. The conversion of high activity wastes to the solid form has some disadvantages including particularly the production of additional low- and intermediate-level wastes and of gaseous wastes. The additional processing required also causes additional radiation doses. However, the increased safety of the finally stored or disposed waste may well outweigh these disadvantages. The methods of conversion of liquid wastes into solid substances are given in table II.[19]

10. The per cent fraction of total radio-activity contributed by certain fission products of biological interest after various times of cooling is given in table III.[7] Serious attention should be given to the proposal[20] that Cs^{137}, Sr^{90} and other long-lived isotopes be removed from high-level wastes, so that the residue can be finally disposed of after a period of about fifteen years. Additional problems are posed by the presence of alpha-emitting transuranic isotopes of long half-life.[21]

Liquid wastes of intermediate- and low-level activity

11. Low activity wastes can often be disposed of directly in the soil, rivers or seas. The quantity of waste which can be disposed of in this way depends on the radio-active components of the waste and on the capacity of the environment to absorb or disperse these components without causing excessive radiation dose to man or harm to the environment. If the amount of waste for disposal exceeds the estimated capacity of the environment, then the waste must be treated to remove part of the radio-activity through concentration. The concentrate can then be stored or transferred to other parts of the environment better able to receive the radio-activity. Intermediate-level wastes almost always require treatment in this way. A relatively complete decontamination can be achieved only by using a combination of methods, the choice of which depends on the composition of the wastes. The efficiency of decontamination methods is given in table IV.[22]

Solid wastes

12. Solid wastes include contaminated equipment, process wastes such as slags, contaminated laboratory wastes, and the concentrates from some types of treatment of liquid wastes. Depending on the activity and the available environmental conditions, solid wastes are either permanently stored, e.g. in concrete-lined trenches, or buried with or without containers, or dumped on the sea-bed in drums or concrete containers. They are often processed to reduce their volume and to simplify the subsequent disposal operations. Such processing includes incineration and baling and usually produces secondary gaseous or liquid wastes which have proved to be of little hazard.

13. Typical quantities of liquid and solid radio-active wastes discharged into rivers, seas and oceans from some of the establishments of the United Kingdom Atomic Energy Authority and United States Atomic Energy Commission are given in table V.[17]

Disposal of radio-active wastes into rivers

14. Studies of the biology of river waters into which radio-active wastes are discharged have indicated that radio-nuclides are strongly concentrated by river organisms, both plant and animal. As examples, observations made at Hanford and at Chalk River will be reported.[23-25]

15. Low-activity cooling water from the reactors at Hanford is discharged, after a short delay, in retention basins into the Columbia River. The activity decreases at points downstream from the discharge point because of radio-active decay and adsorption onto sediments.[23] Estimates have been made of the radiation doses to people living in downstream communities and it has been found that in spite of some very high concentration factors[24] in individual river organisms the principal sources of radiation dose to man are drinking water and a species of whitefish. The use of the river for irrigation and the transfer of radio-active materials to the sea and their reconcentration in marine organisms have been shown to contribute extremely small radiation doses to man.[23]

16. At the Chalk River plant the effluent is diluted by large volumes of water used for cooling the reactors before it enters into the Ottawa River. The concentration of the beta-gamma emitting radio-nuclides is equal to 2×10^{-8} μc/cc upstream from the plant; at a distance of 1.6 km downstream from the plant, the concentration is 3×10^{-8} μc/cc.[25] Sr^{90} in excess of that attributable to fall-out was occasionally observed in fish caught in the locality of the reactor outfall.

Disposal of radio-active wastes into seas and oceans[26]

17. Two methods of disposal of radio-active wastes into seas and oceans are used at the present time. The first consists of the direct discharge of liquid wastes from atomic plants into coastal waters; the second of the dumping of solid wastes on the bottom of the sea after sealing in appropriate containers, thus delaying the entrance of radio-active substances into the water masses. In this connexion the oceans can be considered from two points of view: as a dilution medium for radio-active waste and as an area of temporary isolation in which radio-activity can decay before escaping to the water and ultimately returning to man.

18. While the possibilities of the ocean as a medium for dilution are great, it is obvious that uniform dilution of the global quantities of radio-active wastes in the ocean is highly improbable both because of the slow rate of mixing of water and because of concentrating effects. Among the factors which influence the fate of radio-active wastes in sea water are the physical and chemical state of radio-nuclides and also oceanographic conditions. The possible physical states of elements in sea water are: ionic, colloidal, and particulate.[27] Elements in ionic form will be diluted better, but as they remain longer in solution they may enter in zoo- and phytoplankton. Elements in particulate form or those which tend to be absorbed by particulates in the sea will have a tendency to settle on the sea-bed, which will lead to a higher concentration of radio-activity at the bottom as compared with the rest of the sea. Radio-nuclides in particulate form may then be removed by filter-feeding marine life and so become available to the larger marine fishes. Thus, radio-active materials may enter bottom sediments and in some form become available to bottom-dwelling marine life.

Mixing process between deep water and surface water of the oceans and "biocirculation"

19. In considering disposal of radio-active wastes by burial in ocean depths, it is necessary to examine the possibility of exchange between deep and surface waters of the ocean. Two points of view exist.[28] The first maintains that the replacement of deep waters in the ocean takes place comparatively rapidly, in perhaps forty to fifty years. This point of view is supported by observations and calculations regarding dissolved oxygen and phosphate, and other factors present in the ocean. The other point of view holds that the replacement of deep waters in the ocean, and consequently the time required for any contamination from the depths to come to the surface, takes place much more slowly, over a period of several hundred years, or even 1,000 or 1,500 years. This opinion is supported by studies conducted with carbon-14 and radium. In addition to the movement of radio-active nuclides due to vertical transfer of water layers, "biocirculation"[29-30] also must play a role.

20. It is now clear that the deep waters of the oceans cannot be regarded as isolated from the surface waters. Waste disposal in the deep water in containers must therefore be treated as a form of temporary storage, the storage period depending both on the life of the container and on the rate of transfer to the surface waters. In addition, the process of transfer will result in substantial dilution.

21. Experiments[31] have indicated that the expected life period of metal drums because of corrosion in sea waters is not more than ten years, whereas concrete containers may last as long as thirty years. One container described in the literature[31] is capable of withstanding high pressures and corrosion, so that its expectation of life at the sea bottom is 1,000 years.

22. Since 1946 the United States Atomic Energy Commission has been disposing of relatively low-level radio-active waste products at sea off the Atlantic and Pacific coasts of the United States. Most of these wastes were packaged in 200 l. steel drums with encased concrete drums, and preformed, reinforced concrete boxes were used in some instances. During three oceanographic cruises[32] in March, April and November 1960, samples of sea water, sediments and marine life were collected for the purpose of measuring their radio-activity level. Bottom photographs were taken and documentary motion pictures of the April cruise were filmed. Different seasons of the year were chosen for the cruises in order to detect seasonal differences in levels of contamination. Water depth at all sites was 1,800 m. or greater. The three areas of survey were two disposal sites and the control area off Point Arguello, between the two disposal sites. In general, the results indicated that within experimental error, no radio-activity was detected in excess of the background levels.

23. At the present time, since many factors are still unknown to us and few data on the question of disposing of sealed wastes in ocean depths are available, it is difficult to reach definite conclusions on the suitability of such practices for all types of waste. At present, however, only small amounts of radio-active material are being deposited in the ocean and before this practice could be extended to the high activity waste from large-scale nuclear power programmes, much more investigation would be required into the processes of dispersion and reconcentration. There is still substantial disagreement[33-36] on the validity of deep ocean disposal, but even with the assumption of a very rapid mixing of the deep water and the surface water the present practices have so far given rise to exceedingly small radiation doses to man.

Disposal of radio-active wastes on land

24. Like the ocean the land also can be considered both as a place for ultimate disposal through isolation in special geological formations and as a medium for dispersion of low-level radio-active wastes. In the latter case there is also some degree of isolation by adsorption of the radio-activity on to the soil as well as dispersion and dilution in the ground water. In rare cases substantially all the radio-activity is retained by the soil and only a purified waste reaches the ground water. This situation occurs at Hanford where some quantities of radio-activity are released into the ground and no fission products have been observed to penetrate into the river waters.[23] Direct disposal of low-level liquid and solid wastes into the ground is practised at the present time, and the isolation into special geological formations is in the state of development.

Direct disposal of low-activity wastes into superficial permeable layers of the ground

25. Disposal of low-level liquid radio-active wastes to the ground is founded on the ability of various earth materials to remove and retain fission product cations. Some years of practical experience in the controlled disposal of wastes to the ground at the Hanford Works, Oak Ridge National Laboratory, and Savannah River Plant have demonstrated the feasibility, safety and economy in the disposal of at least limited volumes of some types of liquid wastes.[37]

26. The binding capacity of soil for radio-nuclides depends on the composition of the soil and on the properties of the discharged wastes. Strontium is well sorbed by montmorillonite, kaolinite, mica, hydromicas, peat, phosphorite and nepheline syenites.[38] Caesium, as a rule, is very well retained by soils, and the extent to which it is retained depends on the mineral content of the soil. It has been established that the most suitable types of soil columns for the decontamination of liquid wastes are those composed of vermiculite overlaying solid phosphates, which in turn lie on coarse-grained gravel.[39]

Isolation in special geological formations

27. It has been proposed to discharge liquid wastes even of high activity into various rocks, salt formations, limestone, shale formations, gypsum, sandstone and other impermeable geological formations.[40-41] All these methods are at the experimental stage. Of all the indicated geological formations, the most promising are sandstone and salt formations.

28. Deep well injections of radio-active materials into porous geological formations[40-43] are suitable for regions which have porous rock, such as sandstone, under which is a layer of impermeable material such as shale. Sandstone possesses several desirable properties, such as considerable heat conductivity, stability in acids; its porosity reaches 10-30 per cent; it has a fairly high ion-exchange capacity (20-30 milligram equivalents per 100 g.).

29. Disposal into natural salt formations provides one of the most interesting possibilities.[44-46] The method has several geological and operational advantages and is expected to provide a high degree of isolation. Analytical studies indicate that it is possible to store two-year-old 10,000 megawatt-day/ton, 3,200 litre/ton waste in a sphere about 3 m. in diameter. Structural properties and thermal conductivity of rock salt are not changed to any significant extent under the influence of high doses of radiation. The chemical interaction of liquid wastes with salt produces chlorine and other gaseous compounds, but their quantity is not very great.

Conclusion

30. Information on the contamination of the environment through disposal of radio-active wastes is very limited and only for few areas are relevant data published periodically. In even fewer cases is the published information sufficient to allow any assessment of the resultant radiation doses to man. These cases represent major releases of radio-activity into the environment and it has been shown that the resultant radiation doses to man are small.[18] Other releases of radio-active waste result in even smaller doses and present waste disposal does not make a significant contribution to man's exposure to radiation.

31. The problem of disposing of radio-active waste will assume increasing importance with the development of atomic energy which is expected in the next few decades. It has been estimated[47-48] that the thermal power produced by atomic plants will reach 700,000 megawatts by the year 2000 and will be accompanied by billions of curies of accumulated radio-activity. Almost all the resulting radio-active material will be sent to permanent storage and improved storage methods are being investigated. It is also likely that there will be an increase in the amount of radio-activity dispersed into the environment not only from fuel-reprocessing plants but also from the increasing uses of isotopes in industry and medicine. The control of such discharges and the assessment of the resulting radiation doses to man will thus become increasingly important.

32. Most of the present practices for the disposal of low activity wastes are satisfactory provided that they are subject to close and continued control. In some cases this control should include appropriate environmental monitoring and the primary aim of this monitoring should be to establish that the disposals cause no unacceptable radiation doses to man. In the case of the majority of the industrial and medical applications of isotopes, simple procedures controlled by suitable sanitary standards[49-53] can be used for disposing of radio-active wastes without the need for a complex environmental monitoring programme.

33. The release into the environment of the principal fission-product wastes from the large scale production of nuclear power cannot be considered until substantially more information is available on the behaviour of such fission products in the environment.

II. Releases from accidents in nuclear reactors

34. The release of radio-active materials as a result of nuclear accidents represents a situation that must be considered in connexion with its potential effects on man and his environment. Of the six major nuclear accidents to date[54] only the accidents at Windscale and at Chalk River led to a substantial release of radio-active nuclides.[55-56]

35. The accident at Windscale was caused by local overheating of the uranium fuel elements during the annealing of the graphite moderator of an open air-cooled reactor. The amount of radio-activity released during the accident is not known precisely, but approximate estimates were made from the measurements of the radio-active iodine deposited on the ground and from measurements on air filters obtained both in the United Kingdom and in Continental Europe. The following list shows estimates of the amounts of various isotopes released:

	Curies
Iodine-131	20,000
Tellurium-132	12,000
Caesium-137	600
Strontium-89	80
Strontium-90	2

36. During the six weeks after the accident, over 3,000 samples of milk were analysed. The I^{131} content of milk rose to a maximum three days after the accident when the highest levels recorded were 1.4μc/l. The levels of I^{131} in samples of drinking water obtained from reservoirs, and from streams feeding reservoirs and water taps, varied from below the threshold of detection (about

100 μμc/l) to about 1,000 μμc/l. Samples of eggs, vegetables and meat from the more highly contaminated areas were examined. They also were shown to be contaminated with I^{131}, but contributed much less to the diet of the population than did milk.

37. Before the accident the ratio of Sr^{90}/Ca was 44 μμc/g in milk from a farm within a quarter of a mile of the perimeter of the Windscale Works. Shortly after the accident values up to 115 μμc Sr^{90}/gCa were observed in milk from the farm nearest the plant. It was also found that in the area of highest contamination, the maximum levels of Cs^{137}, Ru^{103} and Ru^{106}, and Zr^{95} in grass were 0.25, 0.21 and 0.3, μc/m² respectively.

38. The only control measure needed as a result of the accident was the control of the consumption of milk and vegetables from an area of approximately 500 square kilometres. The opinion was expressed in the official report following the accident that this control measure had been adequate and that it was highly unlikely that any harm was done to anybody as a result of the accident.

39. Most reactor accidents have taken place in experimental reactors or in reactors cooled by the old-fashioned flow-through system rather than in the more modern power generating facilities where the coolant is recirculated. The probability of other types of accidents occurring can only be assessed on the basis of past experience. This is still limited but suggests that releases of such a nature as to cause concern for the health of individuals in the population are extremely rare. It is also likely that carefully planned emergency measures can substantially reduce the radiation doses which would otherwise result from accidental releases.

TABLE I. SOME EXAMPLES OF RELEASES OF GASEOUS WASTE FROM ATOMIC ENERGY PLANTS

Site	*Amount of waste and radio-active content*
United Kingdom	
Springfields (feed material production plant)	Approx. 1 c/y, alpha
Capenhurst (gaseous diffusion plant)	Approx. 0.1 c/y, alpha (uranium)
Calder Hall (nuclear power station)	10 c/hr, A^{41}
Chapelcross (nuclear power station)	10 c/hr, A^{41}
Dounreay (reactor research centre)	0.5 mc/hr, A^{41}
Harwell (nuclear research centre)	30 mc/y; beta; 1 mc/y, alpha; 50 c/hr, A^{41}
Amersham (isotope production plant)	15 mc/wk, I^{131}
Aldermaston (nuclear weapon research centre)	20 mc/y, beta; 3 mc/y, alpha
United States of America	
Hanford (plutonium production plant)	1 c/d, I^{131}
Idaho (reactor testing station)	100,000 c/y beta, mainly very short half-life, and noble gases
ORNL (reactor development and chemical processing laboratory)	0.25 c/y, alpha (uranium)
Brookhaven (nuclear research centre)	700 c/hr, A^{41}

TABLE II. POSSIBLE METHODS OF CONVERSION OF WASTES TO SOLID FORMS

Preparation containing fission products	Metal oxides dried at 200–250°C	Metal oxides calcinated at 500–700°C	Calcinated clays	Cement blocks	Molten salts	Preparation type glass
Difficulties in the preparation process	Considerable dust	Dust	Limited exchange capacity of clays	Must be mixed	Corrosion of the equipment	High temperature (> 1000°C)
Volume variations	Reduction up to 100 times	Reduction up to 100 times	Reduction up to 50 times	Increase up to 30–50%	Reduction up to 70 times	Reduction up to 350 times
Separation of gaseous products in radiolysis	Yes	No	No	Yes	Yes	No
Heat resistance	High	High	High	Medium	Low	Very High
Heat conduction kilocalorie/metre/h/C°	0.05	0.03	0.05		About 1	Up to 2
Transfer of fission products into water	Considerable	Appreciable	Small	Small	Soluble	Very small

TABLE III. COMPOSITION OF FISSION PRODUCT MIXTURE AFTER ONE-YEAR IRRADIATION OF FUEL ELEMENTS BY 3×10^3 THERMAL NEUTRON FLUX AND VARIOUS TIMES OF COOLING

Isotope	*Half-life*	*Approximate % of total FP activity after cooling*		
		100 days	*3 years*	*30 years*
Cs^{137}	26.6 years	< 2	15	~ 49
Sr^{90}	28.0 years	< 2	15	~ 49
Pm^{147}	2.6 years	3	15	< 1
Ce^{144}–Pr^{144}	290 days	45	50	—
Kr^{85} (gas)	10.3 years	< 1	1	< 1
I^{131} (gas)	8.1 days	< 1	—	—
Zr^{95}–Nb^{95}	63 days	33	—	—
Ba^{140}–La^{140}	12.8 days	< 1	—	—
Ru^{103}–Rh^{103}	41.0 days	5	—	—
Ru^{106}–Rh^{106}	1.0 year	2	3	—
Sr^{89}	54 days	7	—	—
Xe^{133} (gas)	5.27 days	< 1	—	—

TABLE IV. EFFICIENCY OF DECONTAMINATION METHODS OF LIQUID WASTES

Treatment	*Unspecified alpha-removal*	*Unspecified beta-gamma-removal*
$FeCl_3$	97%	50%
$BaCl_2 + Fe_2(SO_4)_3$	99%	98%
Lime soda-softening process	70–99%	50–80%
40-80 ppm Al + activated silica (5-10 ppm SiO_2)	80%	65%
20 ppm Al + lime or Na_2CO_3	90%	70%
40 ppm Na_3PO_4 + lime + tannic acid	98%	75%
100 ppm Na_3PO_4 + lime or NaOH	95%	75%
Phosphate treatment followed by sulphide treatment	99%	90%
Phosphate treatment followed by vermiculite columns	99.95%	99.36%
Precipitation and electro-de-ionization	99–100%	99–100%
Ion-exchange resins	10^2–10^5	10^2–10^4
Mixed bed	10^5	10^5
Evaporation	10^4–10^6	10^4–10^6

TABLE V. EXAMPLES OF LIQUID AND SOLID WASTE DISPOSAL FROM SOME ATOMIC ENERGY INSTALLATIONS

Site	*Type of waste*	*Amount and radio-activity content*	*Method of disposal*
United Kingdom			
Springfields	Liquid	$2.5 \times 10^6 m^3/y$; 50 c/y alpha; 1,500 c/y beta	Pipeline to tidal estuary
Capenhurst	Liquid	$2 \times 10^6 m^3/y$; 1 c/y alpha (uranium)	Open brook to tidal estuary
Windscale and Calder	Liquid	$8 \times 10^6 m^3/y$; 90,000 c/y beta; 40,000 c/y Ru; 1,500 c/y Sr^{90}; 70 c/y alpha	Pipeline to open sea
Chapelcross (1960)	Liquid	$3 \times 10^4 m^3/y$; 4.5 c/y alpha and beta; 80 mc/y Sr^{90}	Pipeline to tidal estuary
Dounreay (1959–60)	Liquid	$10^6 m^3/y$; 40,000 c/y beta; 20 c/y Sr^{90}; 5 c/y alpha	Pipeline to open sea
Harwell	Liquid	$7 \times 10^6 m^3/y$; 15 c/y beta; 0.5 c/y Sr^{90}; 0.02 c/y alpha	Pipeline to River Thames
	Solid	800 tons/y; 80 c/y beta; 4 c/y alpha	Dump in light drums on bed of English Channel
	Solid	50 tons/y; 1,000 c/y beta; 200 c/y alpha	Dump in strong drums on bed of Atlantic Ocean
Aldermaston	Liquid	$5 \times 10^4 m^3/y$; 0.02 c/y beta; 0.06 c/y alpha	Pipeline to River Thames
	Solid	400 tons/y; 2 c/y alpha; 0.5 c/y beta	Dump in light drums on bed of English Channel
	Solid	50 tons/y; 200 c/y alpha; 15 c/y beta	Dump in strong drums on bed of Atlantic Ocean
United States of America			
Hanford (1959)	Liquid	3,000 c/d beta; 1,200 c/d Cr^{51}; 70 c/d Zn^{65}; 0.2 c/d Sr^{90}	Pipeline to river
ORNL (1954–57)	Liquid	$10^6 m^3/y$; 250 c/y beta; 50 c/y Sr^{90}	Discharge to local stream
Brookhaven (1957–58)	Liquid	$5 \times 10^6 m^3/y$; 0.1 c/y beta	Discharge to stream
	Solid	1,000 c/y	Dump in drums on bed of Atlantic Ocean

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