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ABSTRACT

This booklet is a summary of an international symposium, held in August 1970 in New York City, on the environmental aspects of nuclear power stations. The symposium was convened under the sponsorship of the International Atomic Energy Agency (IAEA) and the U.S. Atomic Energy Commission (USAEC). The information is presented in a condensed and readily understandable form, and it is hoped that it will be useful to those interested in a summary view of the public health and environmental aspects of nuclear power production. Contents are organized according to major headings as follows: "The Role of Atomic Energy in Meeting Future Power Needs," "Radiation Protection Standards," "Safe Handling of Radioactive Materials," "Other Impacts," "Public Health Considerations," and "Summary." Included in the summary are lists of "pertinent publications" of the IAEA, the World Health Organization (WHO), other international bodies, and a list of consultants and contributors. In addition to the symposium summary, this booklet also contains contributions supplied by 28 experts from IAEA and WHO and a number of member states. (LK)

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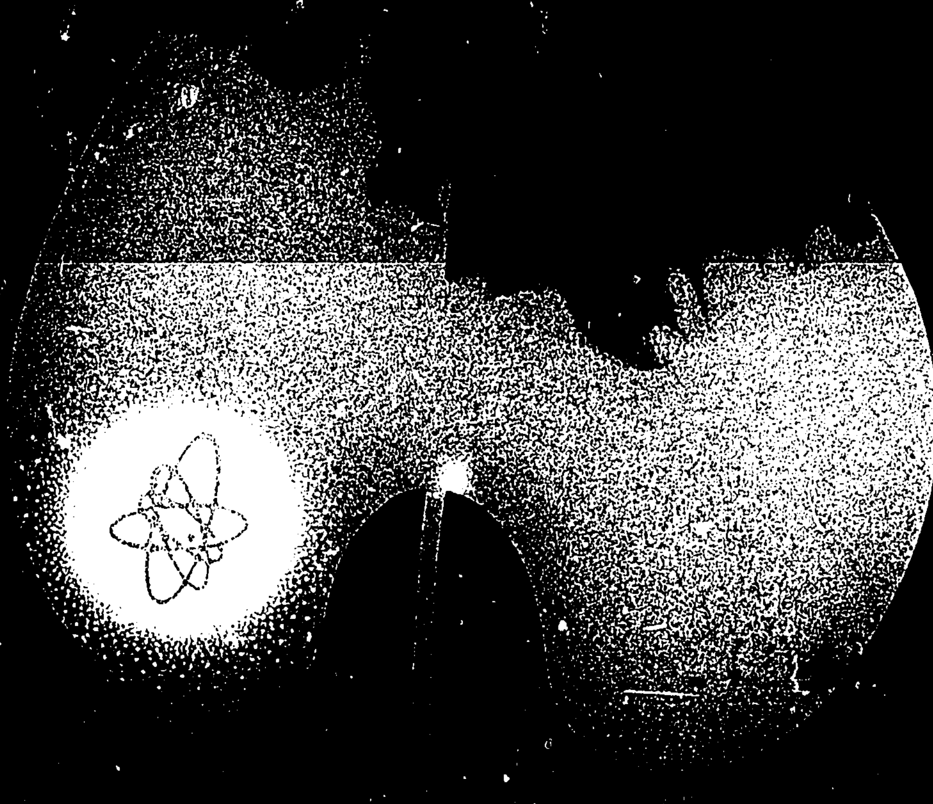

Nuclear Power and the Environment

nuclear power and the environment

Prepared by the IAEA in co-operation with WHO

Printed by the IAEA in Austria

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foreword

Power demands throughout the world are increasing: energy is essential to assure public health and to provide for the quality of life to which man aspires. Nuclear energy, based on fission, is in a position to fill these needs with less detriment to the environment than most fossil fuels.
In the longer term man may need to evolve other sources of power such as fusion energy or solar energy; but these have not yet been developed to a point at which their widespread use in the next few decades can be foreseen.
The nuclear power industry has been developing in an era in which much attention is given to the preservation of public health and environmental quality. No industry, including the nuclear industry, can truthfully claim to be free from all public health and environmental effects, but the nuclear industry has given serious attention to these problems.

Probably more factual information on the effects of radioactivity has been compiled than for any other potential pollutant.

Biologists have shown that radiation doses as low as 0.5 to 1.0 rad per day administered continuously can give rise to observable genetic and somatic effects in small mammals. These levels are about a factor of 1000 higher than the ICRP annual dose limits for the general public, and nearly 10 million times as high as the average radiation dose increment resulting at present from the operation of nuclear installations. At the very low levels of radiation to which members of the public are exposed the frequency of effects is so low as to be not observable; as a result it is possible neither to prove nor to disprove the actual occurrence of effects at these levels. Radiation protection standards are set on the basis that the effects may occur at low doses in proportion to the effects observed at higher dose rates, but evidence exists to suggest that the effects occur with even less frequency, if at all.

A similar situation exists with respect to accidents. Although there have been malfunctions of nuclear power reactors, in no case has there been a release of radioactivity to the environment in amounts large enough to result in an over-exposure of the public. Because of the excellent record of safety that has been attained, it is not possible to establish quantitatively what the probability of a major reactor accident is, except that it is certainly very low. Engineered safety features continue to be developed to improve even further the reliability of reactors to operate without incident.

Interest in the environmental aspects of nuclear power stations led the International Atomic Energy Agency, in co-operation with the United States Atomic Energy Commission, to convene a symposium in New York on this topic in August 1970. The enthusiastic response both during and after that meeting, and the interest in environmental matters evidenced by the convening of the United Nations Conference on the Human Environment in 1972, led to the decision to summarize the information presented in New York in a condensed and readily understandable form for those not engaged directly in this field of work. The World Health Organization has co-operated in the preparation of this booklet, which is the result. It was planned at a consultants' meeting convened in Vienna in June 1971. Following this meeting contributions to the booklet were supplied by 28 experts from the IAEA and WHO and a number of Member States, and compiled by Dr. D.G. Jacobs, who served as scientific secretary. A second consultants' meeting was convened in January 1972 to review the assembled draft. (A list of consultants and contributors is given at the end.)

Compilation of the booklet presented a number of difficulties. The time period between its conception and its desired date of completion was quite short, especially in view of the number of contributions received. There was an attempt to compile a manuscript which was uniform while at the same time maintaining the character of the various contributions. Further, the interests and technical background of the prospective audience presents a broader spectrum than one would normally try to cover with a single publication. As a result there is more repetition and parallel material in the booklet than one might hope to find — though in part this is deliberate. For example, the third chapter contains more operational details than most readers would require, and we suggest that this chapter could be omitted by non-specialists. The information presented may be of considerable interest, however, to others in the intended audience. The first part of the fifth chapter closely parallels Chapter III with regard to the topics discussed, but the discussions take the form primarily of an evaluation of the public health and environmental aspects of the various operations rather than a description of operations and procedures. We are hopeful that in spite of its admitted shortcomings the booklet will be useful to those interested in a summary view of the public health and environmental aspects of nuclear power production.

No one can profess to be able to quantify at this time all of the public health and environmental effects of nuclear power for the future. The attitude of the nuclear power industry is to proceed with due caution after giving consideration to all facets thought to be potentially detrimental. Concurrently, programmes are conducted to advance our knowledge of the impact of the industry and to improve further its safety aspects, with continued periodic reviews on the basis of new information. In view of their responsibility to protect the health of populations, public health authorities are following continuously the development of new sources of power and their effects on the human environment. The nuclear industry has achieved a commendable safety record to date, and it hopes to continue to set an example of thorough attention to safety which other industries may follow.

the role of atomic energy in meeting future power needs

Civilization has developed largely as man has devised new ways of changing and controlling his environment. He has searched continually for new means of producing energy to help him attain his objectives. In the earliest days he relied directly upon the energy from the sun to provide him with warmth. The discovery of fire was the key to releasing the solar energy locked in plants and trees, by the burning first of wood and later of fossil fuels.

Although water power and wind power had been used industrially for several centuries the industrial revolution began really when man harnessed energy from the burning of fossil fuels to drive machines to do his work.

The changes in man's sources of energy and the rates at which they are consumed have been particularly dramatic over the past century. A hundred years ago wood was the source of most energy, but by 1900 it had been replaced largely by coal. After World War II oil and natural gas supplied an increasing fraction of energy.

Economic progress is usually associated closely with available energy. This is illustrated by a correlation between a nation's per capita energy consumption and its gross national product (see Fig.1). Thus, it may be expected that a major contribution to increases in world energy consumption will come from improvements in the economic conditions and standard of living of developing countries as well as from increases in the world population. World energy consumption during the last two decades has increased very rapidly, by about 8% per year - much faster than the rate of population growth, which has been about 2.3% a year during the same period. It is interesting to note that, although all sectors of energy consumption have been increasing, the greatest growth has occurred in the production of electricity.

Since the beginning of the industrial revolution the impact of man on his environment has grown at an ever-increasing pace. But the rate of industrial development in different places has not been uniform, and while the more highly developed countries are now debating whether and if so how to control their economic growth in order to protect the natural environment, the less developed countries must increase their rate of industrialization if they are to attain comparable standards of nutrition, housing, clothing, public health, education and so on.

The great changes in our environment which have occurred in recent years, and the still greater changes which threaten as higher living standards and the increasing world population demand ever-increasing rates of energy production, have provoked a call for closer control of these changes. This demand is greater at present in the developed countries, where higher living standards and more time for recreation allow man to use his environment more intensively, but there is no reason to doubt that it will spread to the developing countries. It seems no more than common sense to urge that the environment should be harmed as little as possible.

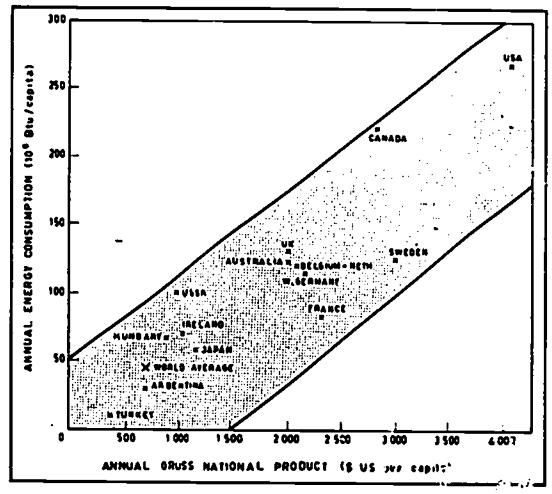
In most places the decision is not whether additional sources of electrical energy should be developed, but how the additional energy which is required can be best produced. Only about one-tenth of the water power potentially available has been developed, but much of the remainder is located in remote areas or is not likely to be developed for economic and aesthetic reasons. Even where hydro-electric power is economically attractive it must be supplemented usually with power obtained from other sources, because its availability varies with the seasons. Solar, tidal and geothermal energy for electricity production are economic only in certain locations or in special circumstances. Thus, most electric power in the near future will be generated in thermal-electric plants based either on burning fossil fuels (coal, oil, natural gas) or on nuclear fission ("burning" uranium, plutonium and perhaps thorium). Usually the selection of plant type is influenced principally by considerations associated with the cost of the plant and its operation, taking into account other factors including the availability of fuel and the reliability of its sources of supply, foreign exchange requirements and availability, and possible effects on employment (for example, in coal mines).

The world needs not only more energy to produce power, it needs as well more efficient means of energy conversion. The major portion of the energy now consumed to produce electricity is wasted as heat, which may affect local ecological systems. Development of more efficient methods for energy conversion would reduce the these losses of energy. Generally less emphasis has been given to development of magnetohydrodynamics and other direct conversion processes, which need to be investigated seriously, than into development of new sources of power. More emphasis might also be placed on improving fuel for power production, for example by gasifying or liquefying coal, in ways which could reduce environmental change.

Recently, however, increased emphasis has been placed on environmental and public health aspects of electric power production in the more highly developed countries. The nuclear power industry has developed in an atmosphere of the utmost caution; probably no other industry has been so safety conscious. The design and operation of nuclear power plants, from their inception, has stressed public safety and environmental protection. Other industries have asserted that their activities are safe, without qualification; the nuclear industry, growing up with statistics, has instead set limits at which the probability of harm is considered acceptably small. Even so, the current trend is toward increasingly strict regulation of releases of both radioactivity and waste heat.

The use of atomic energy as compared with fossil fuel for the production of electricity will affect the environment in a number of ways:

Figure 1



- drastically reducing the mining and transport of fuel;
- increasing by some 50% the heat released into water from power plants which are built initially, though in respect of later plants the increase will be negligible;
- introducing a very small risk of local release of lethal amounts of radioactive substances, by accident;
- requiring small restricted areas for disposal of fission products and for decommissioned reactors;
- slightly increasing the world inventory of krypton, and later tritium, but decreasing the inventory of radon in the atmosphere;
- virtually eliminating emission of particulates, sulphur dioxide, carbon dioxide and mercury to the atmosphere;
- eliminating problems in the disposal of fly ash.

The use of fossil fuels developed in an age which was too hungry for energy to care overmuch about the consequences. But those consequences are now being looked at more closely; there are calls for low-sulphur fuels and for reductions in emissions of sulphur dioxide. The nuclear power industry is under similar, but disproportionately heavy, pressure.

There is need for better knowledge of the relationship between levels of environmental contamination generally and their effects, and for better analysis of environmental problems in terms of costs and benefits. These in turn should be considered in perspective with other claims on resources. Only then can the best decisions, everything considered, be made as to where, when, what size and what type of power plants should be built. The aim of both nuclear and "conventional" industries should be to change the environment as little as is reasonably practicable.

Future world energy needs

During the past two decades electrical energy consumption worldwide has increased at about 8% per year, and this rate of growth has shown so far little sign of slowing down. It is expected that it will be maintained for the next ten years. At present the consumption of non-electrical energy is about three times that of electrical energy, but total energy consumption is growing at a lower rate than electricity consumption. This is reflected in current growth rates of about 3.6% per year for world coal production and of about 6.9% per year for world crude oil production.

Projections for the longer term are made usually on the assumption that the rate of growth in demand for electricity will decrease as population growth rates decrease and as some "saturation" effects are felt, when per capita consumption of electricity reaches higher levels than at present. For example, electricity production in Japan increased at an average rate of 12.4% per year from 1959 to 1968, but it is expected that this rate of increase will fall to about 7% per year by 1980 and to less than 5% per year by 2000. The growth rate in developing countries is likely to be considerably higher than that in industrialized countries during this period.

If one assumes average growth rates of 8% per year until 1980 then of 6% per year until the year 2000, world electricity consumption in kilowatts would increase from 4900×10^9 kWh(e) in 1970; to $10\,500 \times 10^9$ kWh(e) in 1980; to $33\,600 \times 10^9$ kWh(e) in 2000.

World energy resources

It is estimated that reserves of mineable coal total between 4 and 8×10^{12} metric tons. At present rates of increasing annual consumption this would all be consumed before the year 2100. More reasonable projections are that the rate of increase in consumption will begin to decrease before 2000, and that coal production will probably "peak" at about 2100 to 2150 then gradually decrease. At this rate most of the world's coal resources would be exhausted by 2300 to 2400.

Estimates of recoverable petroleum are in the range of 1.3 to 2.1×10^{12} barrels. Even if present rates of increase in consumption begin to decrease in the near future it is estimated that oil production will peak by 1990 to 2000, at a level less than three times the present level, and then decrease. This would exhaust most of the world's oil resources by the year 2025.

The world's potential water power capacity is about 3×10^6 megawatts electrical output (MW(e)), of which less than 10% (principally in Europe and North America) has been developed so far. Presently this constitutes about 28% of the total electrical capacity. By the year 2000 it is estimated that about one third of the potential water power capacity will have been developed, at which time it will constitute only about 14% of the total electrical capacity. Increasingly in some developed countries there are objections to development of hydro-electric power in that this requires the construction of large artificial lakes. Most of the undeveloped water power is in the developing countries.

Solar energy, despite its large magnitude, is both intermittent and of low areal density, and is thus not promising as a source for economic large-scale power production in the near term – although on the basis of recent development it offers hope for the future. Geothermal and tidal energy potentials are relatively small, and are available only in certain locations.

The amount of energy from nuclear fission potentially available in world uranium and thorium resources is several orders of magnitude greater than the amount of chemical energy in fossil fuels. Present-day types of nuclear power reactors using uranium-235, however, release only about 1% to 2% of the potential energy; and for reasons of current economics can use only high-grade uranium ores. On this basis large-scale nuclear power production using uranium-235 would not be expected to last for more than about a century. Breeder reactors are being developed, however, and are expected to become a commercial reality in the 1980s; these reactors will be able not only to release most of the potential nuclear energy, but also to use economically large amounts of uranium-238 and thorium which exist, providing reserves for several hundred years or longer depending on assumptions made as to population growth and per capita electricity usage.

Economic production of electrical energy based on nuclear fusion is at present only a hope for the future. If the deuterium – deuterium fusion reaction can be harnessed the seas constitute a much larger potential source of energy than any of the others mentioned above. If, however, the fusion reaction used is based on deuterium and tritium produced from lithium-6, which seems to be the easier route, the potential energy available will be limited by the amount of lithium-6 which may be drawn upon. One estimate is that the potential resources of fusion energy in this case would be about equal only to fossil fuel resources.

The market price of fossil fuels will most certainly increase as the more easily recoverable resources are used up. The same is true of uranium and thorium ores, but the cost of fuel is a small fraction of the costs of nuclear power, whereas it is the largest part of the cost of "conventional" power, derived from fossil fuels.

The projected role of nuclear power

The primary role of atomic energy is most likely to be in electric power production, though dual-purpose plants will also supply some heat for desalination, space heating and industrial applications. Other uses, such as ship propulsion, will be small relative to electric power production.

Atomic energy is already economically competitive for base-load application in electrical grids large enough to accept unit sizes of about 500—600 MW(e) or larger, and there are indications that nuclear plants in the 200—400 MW(e) range may become competitive in some developing countries. It seems likely that nuclear plant orders will account for half the capacity of all orders in some industrialized countries during the next decade, and that total installed generating capacity worldwide will be 50% nuclear by 2000. [It should be noted that since nuclear plants will be used mostly for base-load application they will generate then more than 50% of the total electricity produced.]

For the reasons listed below it is predicted that nuclear power will account for an increasing fraction of new plant orders, reaching up to 90% of new plant orders by the year 2000:

- the long-term trend in the cost of fuel is upward for both fossil and nuclear fuels, but the cost of nuclear power is much less sensitive to the cost of fuel. This will be true to an even greater extent for breeder reactors.
- transportation costs are a large fraction of the delivered costs of fossil fuels, but only a small part of nuclear fuel costs. In addition, one must consider not only the costs involved in transportation, but the feasibility of developing further transportation systems to move the huge amounts of coal that would be required if nuclear power were not developed.
- environmental protection requirements may add substantially to both capital and operating costs of fossil-fuelled plants. In some countries, too, the costs of coal are already increasing as a result of measures taken to improve safety in coal mines, and the need to restore strip-mined areas. Even with improvement of working conditions in mines there may be problems in finding enough miners. Nuclear plants, however, have been regulated stringently from the beginning and additional requirements which may be imposed are expected to involve relatively smaller cost increases. Enactment of increasingly more stringent air quality standards in industrialized countries could accelerate the trend toward nuclear power plants.
- it is said increasingly often that coal reserves should be conserved as a resource for use in the chemical industry, rather than being used as fuel.

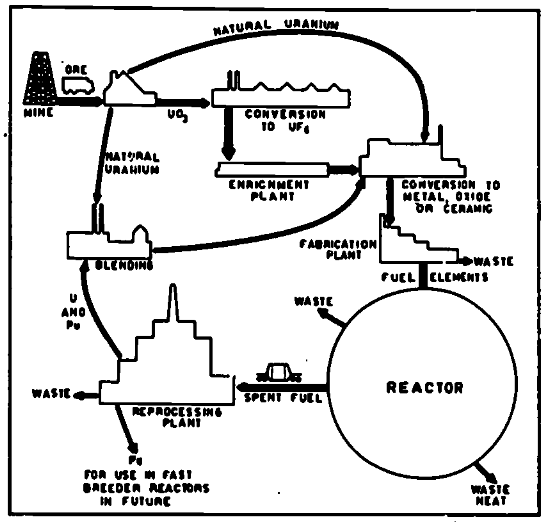
It should be stressed that nuclear and conventional fuels do have a complementary role to play, as well as a competitive one. Because of the way in which load varies with time in an electrical grid, and the nature of the economic characteristics of nuclear and fossil-fuelled plants, it is most likely that the economically optimal system will consist of a balanced mixture of base-load nuclear plants and peak-load fossil-fuelled plants. In some countries the balance may be affected further by alternative sources of energy and the state of their technological development.

The Nuclear Fuel Cycle

The basic fuel for nuclear power plants today is uranium; thorium will become important in a breeder reactor economy. After uranium ore is mined the uranium is separated from the ore in the form of a concentrated oxide. (See Fig.2) For the nuclear reactors most commonly used at present it is necessary also to enrich the natural uranium slightly, that is, to increase the ratio between the fissionable isotope (uranium-235) and the 140 times more plentiful fissionable isotope (uranium-238), which is not easily fissionable but is fertile. This is accomplished by converting uranium oxide into gaseous uranium hexafluoride (UF_6) and passing this through diffusion equipment in which the relative abundances of the lighter and heavier isotopes are varied. Gaseous diffusion plants are operated at present in five countries. In due course they may be supplemented by gas centrifuge plants for uranium enrichment which are now being developed.

The enriched uranium hexafluoride is processed chemically to metal or oxide, which are then fabricated into fuel elements and clad with a gas-tight metal tubing. The fuel elements are

Figure 2: The nuclear fuel cycle



transported to the power station for loading into the reactor.

Up to this point in the fuel cycle all of the waste products contain only naturally-occurring radionuclides and products useable as fuel which are recycled from fuel reprocessing. The radiological problems that arise are due only to the concentration and re-distribution of these radionuclides. However, in the reactor the fuel undergoes nuclear fission, in which the fuel splits into radioactive fragments and energy is given off in the form of heat which is used to convert water into steam for driving the turbines which produce electricity . . . Radioactive materials are also produced in the reactor by the interaction of neutrons emitted during fission with corrosion products, impurities, fuel cladding and structural materials.

"Spent" fuel elements, in which only a fraction of the uranium has been consumed, are removed periodically from the reactor and replaced with fresh ones. The remaining uranium, the fission products (including gases) and plutonium formed during reactor operation are retained essentially within the fuel cladding. Normally it is desirable from the economic point of view to reprocess the spent fuel to recover the valuable uranium and plutonium. These can then be returned to a fuel element fabrication plant for manufacture into new fuel elements, or the uranium may be returned to a gaseous diffusion or other plant for re-enrichment. The fission products and the remaining transuranic elements are removed and processed so that some of them can be used in industry, research and medicine; the remainder are contained and manag[illegible] he long term as discussed later in this text. [illegible] plutonium produced from the uranium-2[illegible] the initial fuel is especially important, for this may be used as new fuel for present power reactors and also for future fast-breeder power reactors.

Well over 99.9% of the radioactivity generated in power reactors is retained within the fuel elements until they are reprocessed. Because of this, and the fact that one fuel reprocessing plant may serve a large number of power reactors, it is at this stage of the fuel cycle that long-term management of radioactive wastes becomes especially important. Low-level wastes may be released to the environment, following appropriate treatment, if they can be safely diluted and dispersed. The major objective of the high-level waste management programme is to keep the great majority of the potentially dangerous wastes isolated from the human environment for a time long enough to allow them to lose their radioactivity through decay. As discussed later, the techniques used to accomplish this degree of isolation differ depending on the geologic conditions in the various countries where fuel reprocessing is carried out.

One ton of slightly enriched nuclear fuel will produce about two hundred million kilowatt hours of electricity, which is enough to satisfy the needs of about 70 000 people for a year (this figure is based on present-day per capita consumption in Europe). [See Fig.3]. Reprocessing of this amount of spent fuel gives rise to about 0.4 to 0.8 cubic metres of high-level liquid wastes, or about 0.04 cubic metres of solidified waste.

Environmental Aspects of Nuclear Power Production

As in any major technical enterprise there are environmental aspects of nuclear power production which require particular attention. In this respect the nuclear power industry has been since its inception fully aware of the need to ensure public safety and to prevent damage to property and to the environment as a whole.

Radioactivity

One of the most obvious problems associated with the nuclear power industry is in the generation and potential release of radioactive materials. The rate of generation of radioactive materials in a nuclear reactor is primarily a function of the rate of heat production, and hence electricity

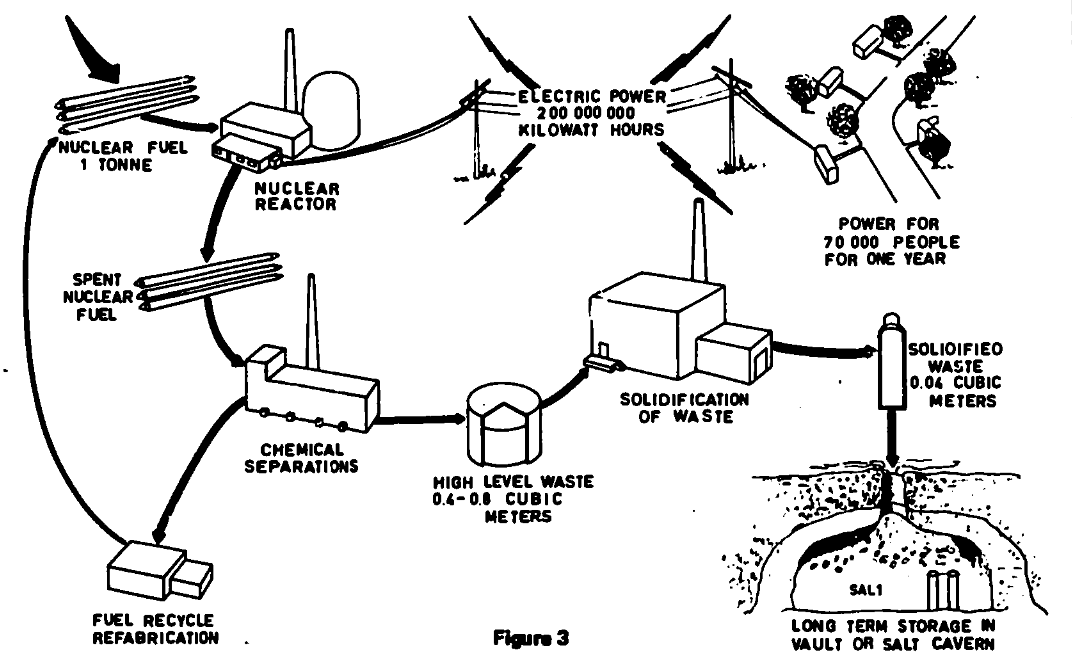


Figure 3

production after making allowance for thermal efficiency.

Provisions are made in the design and siting of power reactors and of ancillary nuclear facilities to cope with potential accidental releases of radioactivity as well as with routine releases. The principal constraints, in general, are imposed by the consideration that must be given to the highly improbable but potentially dangerous serious accident. As a result, radiation doses to members of the public at large during routine operation have been only a very small fraction of those from natural background radiation and of the levels set in internationally accepted radiation protection standards.

The technology required both to prevent accidents and to mitigate their consequences should they occur is fundamental to the designing of nuclear installations in such a way as to afford maximum protection to the environment.

The safety record of the nuclear industry has been particularly noteworthy: the few accidents that have occurred have been well within the capability of the installations concerned to contain the abnormality and to protect the public.

But the projected growth of nuclear power and the potential public health risks involved, however small, require that diligent controls should continue to be practised. The public is quite aware of the risks involved, and it is necessary and proper that the nuclear industry keep the public informed about the careful controls that are exercised to minimize these risks. The timely public acceptance of nuclear power may be as important as is the development of the technology itself.

Low activity liquid and gaseous wastes are released routinely from reactor power stations, fuel fabrication and reprocessing plants after appropriate treatment. Low activity solid wastes, including the residues from treatment of low activity liquids and gases, are generally disposed of by burial in the ground, although some are being disposed of in the deep seas.

High activity liquid wastes arising from fuel reprocessing are concentrated and isolated very effectively in long-term storage; subsequently they may be converted to a solid form and stored in some form of deep repository.

Thermal discharges

No method of converting heat to electricity uses all the heat which is available. Modern steam turbines operating with fossil fuels and using high pressure and high temperature steam attain thermal efficiencies of 40% or more. Most present-day nuclear power plants are thermally less efficient than these modern fossil-fuelled power plants, although they are comparable in thermal efficiency to the average of all fossil-fuelled power plants now in operation. In fossil-fuelled power plants part of the excess heat is released to the atmosphere in the flue gases, whereas in nuclear power plants essentially all of the excess heat is transferred to the cooling water. As a result, a nuclear power plant in which the cooling water is used only in one pass through the cooling circuits (a once-through design) will discharge about 50% more waste heat to the receiving waters than a fossil-fuelled power plant producing an equal amount of electricity. Gas-cooled and liquid-metal-cooled advanced reactors of the future are expected to attain higher thermal efficiencies, equal to or exceeding those of conventional plants.

There is no doubt that the discharge of waste heat into public waters does modify the aquatic environment. The question is whether this modification is perceptibly harmful or beneficial, and whether it affects water use significantly. Knowledge of the aquatic life present in the receiving waters, coupled with use of engineering techniques designed to minimize the impact of the release of waste heat, can enable power plants to meet the desired standards of water quality. If there is not enough water available to meet these standards with a once-through cooling system then provision must be made for alternative systems: for example, cooling towers or cooling ponds are being used in many power plants, both nuclear and conventional, to recycle cooling water and thus reduce the effects of the release of waste heat to acceptable levels.

Transportation

The various components of the nuclear fuel cycle are inevitably at different locations – a power station here, a reprocessing plant there. This may require the transport of nuclear materials, ranging from ores to spent fuel elements and solidified high-level wastes, over large distances. Although the number of such shipments in transit at any given time may become quite high, the accident rate in the transport of hazardous cargoes is much lower than that for normal shipments. The IAEA has drawn up regulations applicable to all modes of transport by normal conveyances which have been widely accepted by national authorities and by organizations concerned with the international transport of goods. The regulations provide for the design and testing of containers for highly radioactive shipments to standards which ensure that even in the event of a serious accident there should be no loss of radioactive material to the environment.

Decommissioning of nuclear installations

This problem is touched on here in order to paint as complete a picture as possible of the difficulties which can arise in connection with nuclear power; it is not so much that its importance is comparable with that of the other problems discussed.

Taking into account the 25 to 35 year life of nuclear power plants, we must expect that in about 1990 a number of power plants will need to be decommissioned, and that thereafter this number will rise rapidly. The decommissioning of power stations, even conventional ones (which are as a rule larger in size than nuclear power plants), is a costly procedure. Despite their smaller size, nuclear power plants would be more costly and difficult to decommission because of the radioactive substances remaining in the structure of the reactor and the primary circuit, although these are only a small part of the whole installation. If there has been an accident in the reactor the problems of dismantling will be more difficult, and if a serious accident has occurred it may be prudent to abandon the reactor in place, taking appropriate precautions to avoid spread of radioactive materials and to restrict access to the area. It can be said that on the basis of present technology the decommissioning of reactors is quite feasible: successful operations of this type have been undertaken (the SL-1 and Elk River reactors in the US, and the Lucens reactor in Switzerland).

The problem now being studied is concerned rather with the ease and cost of operations. It is believed and postulated that some extra means adopted at the design stage could make decommissioning much easier. Even the basic need for complete decommissioning of nuclear power installations is being discussed. It seems quite possible to provide for siting of nuclear power plants in nuclear power "parks" which would continue to be used during long periods of time. New units would be built there to replace old ones, and public access to the site could be restricted, making it unnecessary to remove completely the most complex components of obsolete installations. Many factors enter into this discussion, among them the need for adequate cooling water resources for operating facilities.

radiation protection standards

Introduction

Nuclear power stations are designed and operated in such a way that they release only an extremely small amount of radioactivity to the environment during routine operation or even in the event of a major accident. Almost all radioactivity is prevented from being released by one of the following four mechanisms:

- radioactive decay at the station;
- containment within components during the life-time of the reactor system;
- periodic removal to fuel reprocessing plants within the used fuel elements; and
- disposal in solid waste.

The amounts of radioactivity in gaseous and liquid effluents released to the environment are limited by law in each country to meet standards of radiation exposure of the general public, and make up a very small fraction of the total amount generated.

National radiation exposure standards quite generally are based on recommendations by the International Commission on Radiological Protection (ICRP) for maximum permissible external and internal (i.e., from the intake of radionuclides) exposure. These recommendations have evolved from numerous studies in many countries of somatic effects and hereditary effects (damage to descendants) at high radiation exposures. Information is also obtained from animal research. Dose limits have been established at radiation exposure levels which are considerably lower, at which somatic damage and hereditary effects are believed to be at very low incidence. Maximum permissible body burdens (MPBB) and maximum permissible concentrations (MPC) of radionuclides in air and water have been calculated from these dose limits on the basis of observation of the metabolism, i.e. retention, movement, distribution and elimination of radioactive material from the body of a 'reference man'.

The derivation of radiation protection standards has been clearly formulated in a series of ICRP publications, but it is a complex undertaking. Radiation effects depend on the type of radiation, its intensity, the exposure period, the extent to which the body is irradiated, and a number of factors that affect the radiation susceptibility of a person. In applying information from animal studies to humans differences in metabolism and response must be evaluated carefully. Further, effects at maximum permissible values have been computed by assuming that the ratio of effect to exposure is the same as at the much higher exposures at which effects were observed (the linear dose-effect hypothesis). This calculation is believed to be safe and conservative, although the actual relationships cannot be proved on the basis of direct observation.

The radiation exposure of the public at large as a result of the operation of nuclear power facilities is controlled usually by limiting the rates of release and concentration of radionuclides in effluents so that standards will not be exceeded for the group of persons exposed to the highest radiation levels. Compliance with these limits is checked by measuring the radioactive content of effluents. In addition, environmental surveillance may be undertaken to confirm that environmental reconcentration processes do not lead to undue exposure of members of the public. Although all environmental processes are considered, experience generally has shown that certain radionuclides and environmental pathways make the greatest contributions to radiation dose. These radionuclides and pathways and the population group receiving the highest radiation doses are termed "critical" and are subject to special attention in environmental surveillance programmes. The environment may also be monitored to check on effluent data and to provide direct radiation measurements in emergencies.

In some countries there has arisen recently a growing opposition to the building and operation of nuclear power stations. Concern about radioactivity discharged routinely in effluent air and water has three foci:

- that radiation effects at reported exposure levels could be much more severe than indicated in ICRP recommendations;

- that radiation exposures could be much greater than computed from discharge data; and
- that radiation effects, although believed on the basis of the linear dose-effect hypothesis to occur infrequently, nevertheless could be unacceptable.

Those who challenge the ICRP standards argue that exposure of a large population group to the allowable maximum would increase markedly the number of cancer cases, and would cause thousands of genetic deaths. At least one research worker has carried this general line of argument so far as to calculate a correlation between very low levels of radioactive emissions from power plants (which are a small fraction of natural background) and infant mortality.

The complexity of the subject does not permit an adequate treatment in a booklet of this type, but several key points should be stressed.

When discussing existing radiation protection standards one can state that not all scientists agree about them. As one journalist commented: "When scientists disagree, reasonable non-scientists have to fall back on the faith of the majority." The guidance that forms the backbone of radiation protection standards comes from independent scientists chosen specifically for their competence in the field. No single individual nor single agency has made these basic determinations unilaterally.

The radiation protection standards which are generally acceptable today are by no means fixed and final. Data on the effects of radiation, from both national and international programmes, are reviewed by expert committees on a continuing basis both nationally and internationally.

From the bio-medical standpoint arguments as to the adequacy of current standards centre largely on the calculation of risk for the very low dose range; that is, at the level of the natural background and below. To make such calculations one must make certain assumptions and extrapolate from the region of high dose rates and dose levels, for which there is experimental evidence, to exposure levels at such low dose rates and dose levels that effects, if any, have not been observable. All such calculations contain a degree of uncertainty, and arguments have arisen as to what that degree of uncertainty is. Some even ignore this uncertainty entirely and base their public statements upon the upper values calculated by them, treating them as fact. As one observer has stated: "They put forth their projections not as hypothesis but as fact, saying their mortality rates will — not might — occur." All such calculations, to be meaningful, must reflect the uncertainties involved. Scientists generally use a linear dose/effect relationship to project from the doses at which quantitative information has been obtained to the low dose region. However, ICRP has cautioned that:

"It must be borne in mind that in some instances this may lead to a gross overestimate of the incidence of effects from chronic low level exposure; indeed, some of the effects may not occur at all."

The arguments over accuracy of calculation of risk from exposure at levels comparable to background or lower are somewhat academic for two reasons:

- They led those who first adopted this approach to the assessment of risk to the conclusion that until more is known about low level effects, to be prudent one should not expose people to any higher levels of radiation than is necessary. Although upper limits were identified as a frame of reference these were recommended in accordance with a guiding philosophy which gave encouragement that exposures be kept as low as was practicable.
- People are being exposed to only small fractions of the amounts identified as upper limits as a result of nuclear power production. Radiation protection standards as implemented are serving to keep exposures received by the public as a result of nuclear power production well below the levels identified as the maximum allowable. Such exposures averaged over large population groups are but a small fraction of the natural background, and will continue to remain so for any reasonable projections of the growth of nuclear power production that one can now make.

Concern about possible catastrophic accidents has its source in the expected rapid increase in the number of stations. Speculations as to the frequency of accidents and their possible effects are extensive but arbitrary, in view of the brevity of operating experience — 15 years for a few small reactors and 10 years for some of intermediate size. Until now, no widespread accidental environmental contamination arising from the operation of a nuclear power station has occurred, and no adverse effect on public health has been observed to result from operating such stations. The only such incident that has occurred was at a plutonium producing reactor (at Windscale in the UK) which was not equipped with the engineered safeguards required for nuclear power reactors, and even in that situation there was no demonstrable harm to any member of the public.

Basic Radiation Concepts

Radionuclides are formed within nuclear reactors by several processes. Fission products are generated by nuclear fission within the fuel. Activation products arise through interaction of neutrons with materials — coolant medium, reactor vessel, cladding, gases dissolved in liquid coolant — that surround the fuel. Transuranium elements (neptunium, plutonium, etc.) are formed by neutron activation of the fuel. The fuel itself is composed of natural radioactive material, usually uranium.

Most radionuclides remain in place within fuel or reactor materials. A small fraction leaks from fuel through minute imperfections in its cladding or erodes from other materials or recoils from them, and combines with the radioactivity originating in the coolant medium. Much of this radioactive material, in turn, decays or is retained within the system. A small fraction routinely leaves the system as gaseous and particulate effluents to air, in liquid wastes discharged to rivers, lakes or oceans, and in solid wastes for burial at specially controlled sites. After use, the fuel is first stored at the reactor to reduce its radiation level by decay, and is then taken to a fuel reprocessing plant.

The amount of radioactivity associated with inventories or releases is commonly expressed in curies*. Different radionuclides not only have wide ranges of values for their radioactive "half-lives", the periods during which their activity decays by half, but also for the amounts that may be deposited in different organs of the body, if ingested or inhaled, and in their rates of elimination from the body. To determine biological effects one must know not only about the quantities of the specific radionuclide involved in curies but also the type of radiation emitted as the atoms disintegrate (alpha, beta or gamma), the total amount of energy emitted per disintegration, the rate at which this energy is absorbed in an organ, the biological and radioactive rates of elimination and the mass and radiosensitivity of the tissue involved.

These factors are then considered in the calculation of radiation dose. The basic unit of dose for measuring the ionizing radiation energy absorbed in passing through a medium such as body tissue is the rad§ (one-thousandth of a rad is a millirad, abbreviated mrad). For radiation protection purposes, it is desirable to consider the rads of absorbed energy from each type of radiation weighted by factors characterizing its quality, biological effects, distribution factor and any other necessary modifying factors. The quantity that is obtained by the weighting of the absorbed dose by these modifying factors is called the dose equivalent.

In this paper, the shorter term 'dose' is sometimes used for the sake of convenience, even though the meaning is strictly 'dose equivalent'. The dose equivalont is equal numerically to the dose in rads multiplied by the Quality Factor and any other modifying factors recommended by ICRP. The unit of dose equivalent is the rem. In this way, the biological effect from different types of radiation or from a mixture of radiations can be expressed on a common scale, which has as its unit the rem (one-thousandth of a rem is a millirem, abbreviated mrem).

The Quality Factor for gamma rays and beta particles is 1; and for alpha particles 10. Thus, assuming other modifying factors to be unity, exposure to 1 rad of gamma rays is equivalent to a dose of 1 rem; to 1 rad of alpha particles, 10 rems. Doses described in terms of rems are additive. A person absorbing 1 rad each of alpha and gamma radiation in an organ would receive a total dose of 11 rems in that organ.

Biological Effects of Radiation

Biological damage by ionizing radiation has been studied intensively for many decades. The effects of radiation on biological systems have been examined in animal experiments, radiation accident victims, survivors of atomic bombs at Hiroshima and Nagasaki, patients undergoing radiation therapy, and persons exposed to radiation in the course of their work. Biological effects are classified broadly as somatic, occurring within the exposed individual, and hereditary, those affecting descendants by altering genes. Exposures are classified as acute (brief) and chronic (continuous). An acute exposure at a radiation dose of hundreds of rads produces almost immediate effects, known as the acute radiation syndrome. Most persons incur exposures that are chronic at low levels; effects, if any, may be delayed for decades.

Some typical late somatic effects manifested in man from high doses include leukemia and other malignancies among patients treated by X-rays for spondylitis and among atom bomb survivors, lung cancer in uranium miners, and bone cancer among radium watch dial painters.

* A curie is a special unit of activity equalling 3.7×10^{10} nuclear transformations per second.

§ A rad is defined as the unit of adsorbed dose equal to 0.01 Joules per kilogram in any medium.

Alterations (mutations) of genes can be produced by radiation, as well as by chemical mutagens and physical causes such as heat. Mutations are usually considered to be detrimental. Those occurring in germ cells can be transmitted to offspring; their effects, which range in severity from inconspicuous to lethal, may not be revealed until many generations have passed. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reports that serious genetic detects are observed in about one per cent of live births and that natural radiation can account for no more than a small fraction of natural mutations in man.

Some questions about the biological effects of radiation remain unanswered, particularly those concerning somatic and hereditary damage from continuous doses of radiation not much higher than the natural background. Is there a safe threshold dose for somatic effects – that is, a level below which no effects can be observed? Leukemia induction has been demonstrated clearly at doses above 100 rads, according to the ICRP, but the existence of a threshold dose below this level is still uncertain. UNSCEAR indicates that cataracts occur after chronic exposure to 500 rads of beta or gamma radiation or 200 rads of mixed gamma and neutron radiation. Because of the limitation of numbers in experimental populations, animal studies of genetic exposure fail to indicate a dose or dose rate below which the probability of effect is zero. Some controversy exists among geneticists about this; for example, a recent investigation indicates that among female mice there does occur what is for practical purposes a threshold dose rate.

Some concern is often voiced that additional hereditary damage may be incurred by the general population from proliferating nuclear activities. Not only the affected individual's misfortune but the burden imposed on future society by an increase in the number of persons with mutated genes must be considered as well. A subject of current interest is the amount of exposure equivalent to the "doubling" dose, that is, the additional quantity of accumulated dose to each member of a population within child-bearing age that effects an eventual doubling of the mutation rate. Present estimates, according to UNSCEAR, are that a chronic irradiation of 100 rads or possibly higher is necessary. Since the dose from natural radioactivity is much less than one per cent of this range, it is believed that an additional dose on the order of that from nature would cause no measurable increase in the mutation rate.

There is insufficient information at the moment to give unequivocal answers to all questions of radiation effects. For example, at low doses, effects may vary with the dose rate. Not all forms of injury may be known. To what degree does tissue repair damage after irradiation? Is the frequency of effects greater for persons continuously exposed to higher than normal natural background radioactivity? In view of these incompletely answered questions a conservative approach has been used in arriving at radiation protection standards. In the meantime work to answer these questions is continuing.

Knowledge about the relationship between dose and frequency of effects is required by those responsible for establishing permissible human exposure levels. Studies of abnormally exposed persons mentioned previously have yielded much information, but dose-response estimates based on the data are very approximate due to uncertainties in total dose delivered or total exposure period.

Research with animals has been valuable in confirming the effects from high doses observed in man, but the results cannot be related directly to man due to inherent biological differences. Radiation sensitivity is too variable between species or even strains to enable the drawing of valid conclusions about threshold levels or the occurrence of delayed effects from chronic exposure. Moreover, statistically acceptable studies require vast populations exposed to radiation near background dose levels.

In the absence of definite evidence, frequency of effects can be related to low doses in several ways. A conservative method is to assume no threshold and extrapolate a straight line downward to zero dose from the higher dose-response levels where more data are available. This provides a line of maximum likely risk. On the other hand, one may select a threshold dose level below which no response is believed to occur – an approach used to set tolerance standards for many toxic substances. The latter requires decisions concerning the threshold level and the shape of the dose-response line.

Basic Radiation Protection Standards

The basic standards for radiation protection have been recommended by the International Commission on Radiological Protection (ICRP). The ICRP is an independent body of 13 internationally recognized experts drawn from many countries and a variety of professions – genetics, biology, radiobiology, medicine, chemistry, physics, radiology, engineering, mathematics, etc. The ICRP was formed in 1928 under the auspices of the Second International Congress of Radiology to lay down guidelines to the medical professions for exposures to X-rays and radium. In 1950, the Commission was reconstituted to provide radiation protection guides for the increasing application of the atom for power production, in laboratory research and in industrial processes, and for the handling of radioactive waste, and so on.

The function of the ICRP is solely advisory; it considers fundamental principles upon which radiation control practices can be based. Recommendations by ICRP have no legal force, recognising that the factors affecting risk-benefit evaluations may vary from nation to nation. Many countries have established national committees of experts to assess their own national, economic and social considerations for the formulation of policy and regulations. For example, the United Kingdom has the Medical Research Council's Committee on Protection Against Ionizing Radiation, Japan has the Radiation Council, and the U.S. has the National Council on Radiation Protection and Measurements. The United Nations has authorized the International Atomic Energy Agency to set standards for its operations.

In formulating dose limits the ICRP considers that, if man wishes to obtain the benefits of nuclear applications, he must recognize that there is a degree of risk involved and that the benefits must be worth the assumed risk. According to the ICRP, "the objectives of radiation protection are to prevent acute radiation effects, and to limit the risks of late effects to an acceptable level". For purposes of radiation protection, any exposure is assumed to entail a risk of biological damage, a risk that increases in proportion to the dose accumulated. In other words, the frequency of effects such as leukemia or cataract formation observed at high doses for relatively short periods has been extrapolated linearly to low chronic radiation doses. As discussed previously, this approach is conservative, expressing maximum likely risk and implying that there is no wholly safe radiation dose. The ICRP states in its Report No.9 that, in absence of positive knowledge that a threshold dose level exists, "the policy of assuming a risk of injury at low doses is the most reasonable basis for radiation protection" even though such calculations may over-estimate the real risk involved. Therefore, the basic recommendation of the ICRP is that radiation doses should be as low as is practicable and in any case should not exceed dose limits prescribed for various organs.

The latest dose limit recommendations for somatic effects in individuals and for hereditary effects in whole populations were adopted by the ICRP as from 17 September, 1965, and are published in Report No. 9, referred to earlier. The limits for individuals are expressed as doses permitted to various organs and tissues in the body, considering the radiation sensitivity and size of these tissues.

Two categories of individuals are recognized for dose limit purposes: adults exposed in the course of their work and individual members of the public. This distinction is made because radiation workers constitute a small population that has accepted employment voluntarily and undergoes periodic medical examinations. The hazards to which they may be exposed are anticipated normally and are monitored and controlled to ensure that permissible dose values are not exceeded. The general public, on the other hand, is a much larger population and therefore may accumulate a greater number of radiation effects. Members of this population may have no choice about exposure and may receive no direct benefit from it. They may be exposed environmentally for a greater number of years than the typical duration of employment. In addition, the public includes children and embryos who are more sensitive to radiation, and adults who may be more susceptible to damage. For these reasons, dose limits for individual members of the public are recommended to be 10 per cent of the annual doses permitted for radiation workers. The ICRP recommendations given in Report No. 9 for individual members of the public are listed in Table I.

Table I.
Dose Limit for Members of the Public

Organ or tissue	Dose limit, rem/year
Gonads, red bone-marrow	0.5*
Skin, bone or thyroid	3.0**
Hands & forearms; feet & ankles	7.5
Other single organs	1.5

* Gonads and red bone-marrow are considered to be the critical organs when the whole-body is exposed uniformly; dose limits for these organs also apply to all cases of uniform irradiation of the whole body.

** For children up to 16 years of age the dose limit for the thyroid is 1.5 rems/year.

The most stringent dose limitation is to ensure that the risk of damage to the total present and future genetic structure of the general public remains exceedingly low. The ICRP assumes that hereditary effects are related linearly to the gonad dose. It recommends that the "genetic dose" to the population should be kept to the minimum amount consistent with necessity and should certainly not exceed 5 rems from all sources additional to the dose from natural background and from medical procedures over the normal period of child-bearing, taken to be 30 years. The genetic dose limit is to be applied as an average to the total population, allowing some members, such as radiation workers, to receive higher doses since others are likely to experience lower exposures.

The ICRP deems it important that no one radiation source, such as nuclear power plants, contribute inordinately to the population dose. The commission recommends that any unnecessary exposure to radiation workers and the public alike be avoided and that all doses be kept as low as is readily achievable, taking into consideration economic and social factors.

The dose incurred in any organ or tissue is the sum of exposure from external and internal sources. The total dose, particularly from internal deposits of radionuclides, is difficult to measure directly. Secondary standards have therefore been computed by the ICRP to limit concentrations of individual radionuclides in inhaled air and drinking water, to be used when these represent the major source of radionuclides for the exposed group. Such values are based on primary dose limits considering the half-life, types of radiation, transportability and sometimes the chemical form of the radionuclide, and the fraction absorbed by each organ (or tissue), the period of retention, organ size, and average daily inhalation of air and consumption of water by a 'reference' man. 'Reference' man is a model representing the average anatomical and physiological characteristics of European and North American adults. The organ for which the lowest allowable concentration of a radionuclide is set is referred to as the critical organ. These MPC values for members of the public are also one-tenth as large as those for radiation workers.

Derived Release Limits

The dose a nuclear facility contributes to each member of the public is impossible to determine in actual practice since exposure would need to be measured individually and distinguished from natural and other, man-made contributions. Instead, derived release limits have been developed for application in the facility design and operation to ensure that radioactive discharges do not exceed the primary ICRP dose limits for the public. Such limits consist of upper values for the rates of release of radioactive materials from an installation or for radioactivity levels in environmental media that represent pathways for movement of radionuclides from the source to humans. Derived limits must be promulgated and applied with restraint because a proliferation of them, particularly those developed for local conditions, could lead to confusion that would undermine their purpose.

Derived limits sometimes include values for the radionuclide concentrations in effluents and are set as MPC values for air and water at the boundary of controlled areas around nuclear power stations, atomic research laboratories, etc. They may be established for individual radionuclides or for gross radioactivity; in the latter case the limits are more conservative. In addition or as an alternative, release limits may be set considering the dispersion and concentration of critical radionuclides along pathways to critical populations, so that the discharge limit will not lead to an exceeding of the appropriate dose limit for the general public. For example, at the Windscale reprocessing plant, such release limits have been derived for ruthenium-106 concentrations in Porphyra seaweed from which laverbread is prepared, and for external dose to fishermen from radionuclides retained by silt in the local estuary. The regulatory limits for releases are expressed in curies per unit time, usually three months or a year.

Figure 4: Pathways to man for radioactive releases to air

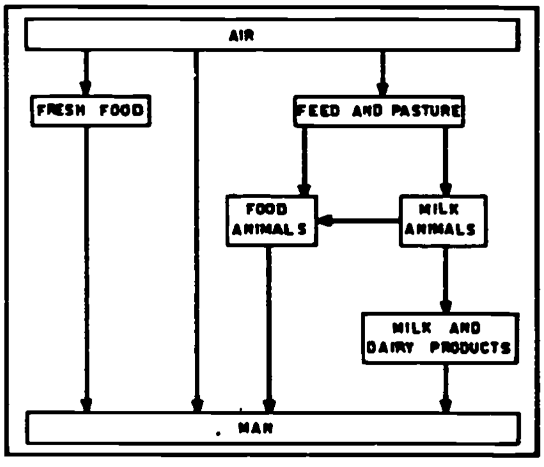
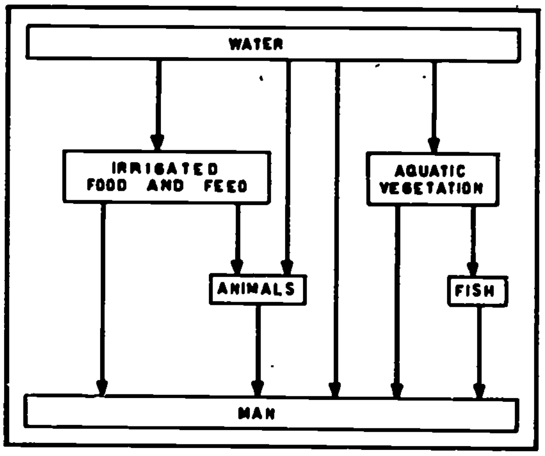


Figure 5: Pathways to man for radioactive releases to water



Various pathways by which radioactivity discharged to water and air reach man are shown in Figures 4 and 5.

The development of derived secondary standards requires quantitative information concerning discharged radionuclides, their environmental behaviour in moving from a source to potentially exposed populations, and the characteristics of the population. Considerable data are available on environmental processes such as atmospheric dispersion, reconcentration by fish, and transfer from cow's feed to milk. Invariably, surveys at proposed facility sites are required to identify critical radionuclides, pathways and populations, and to determine the extent of the effects of local environmental processes on the behaviour of radioactive materials.

Natural Radioactivity

The natural ionizing radiation to which man has been exposed continuously provides a basis for evaluating potential effects from low-level man-made sources. Natural radiation results from cosmic rays which bombard the earth continuously from outer space, and from the decay of radioactive substances on earth. Dose rates from these sources to individuals are highly variable, depending on elevation above sea level, local geology, seasons, dietary habits, time spent outdoors, type of residential construction, and so on.

The average dose rate received annually by the world population from natural sources was estimated for several critical body organs by UNSCEAR in its report to the UN General Assembly for 1966. The data summarized here in Table II pertain to the gonadal dose, which was computed because the gonads are the organ receiving the highest estimated dose.

Cosmic rays striking the atmosphere cause multiple nuclear reactions that yield radiations of many energies. Dose rates to man are highly dependent on altitude and slightly on latitude. At sea level, the dose rate is estimated to be 28 mrad/year at middle latitudes and about 10 per cent lower at the equator. The dose rate approximately doubles for each 1.5 kilometres above sea level for the first several kilometres. Thus, doses from this source are of greater significance to populations living at high altitudes, aircraft crews, air travellers, and space explorers.

Cosmic rays also produce radionuclides through interactions with nuclei in air, land and water. These may contribute to internal human dose through inhalation or ingestion. The most abundant long-lived radionuclide in air from this source is carbon-14 at a concentration of 1.3 to 1.6 X 10^{-12} curies per cubic metre, with beryllium-7 at slightly lower concentrations and considerably smaller amounts of tritium (hydrogen-3), phosphorous-32, and a number of others.

The earth contains other radionuclides believed to have been formed during its creation, long-lived primordial radioactivity derived mainly from uranium and thorium, with small amounts of potassium-40, and traces of rubidium-87, vanadium-50, indium-115 and several others. Uranium and thorium have many decay products, of which radium-226 and gaseous radioisotopes of radon are of particular interest.

All of these naturally occurring radionuclides are sources of external exposure, mostly from ground deposits and to a certain extent from construction materials such as brick, concrete, and granite. Dose rates average 47 mrad/year. This value varies for different regions, being approximately 4 times higher for certain granite regions in France and as high as 290 and 800 mrad/year in monazite sand regions of Brazil and India respectively. Radon gas and its radioactive daughters in air are also external sources, but contribute only a small fraction to the external gonad dose.

The internal dose from natural long-lived radionuclides results mostly from potassium-40, an isotope of elemental potassium. This is a normal component of the body and is maintained at its usual level by intake in food and by metabolic turnover. Carbon-14 and rubidium-87 taken in in food and water together contribute about 1 mrad/year. Radon-222 and a daughter product, polonium-210, taken in mostly from air, contribute about 0.6 mrad/year.

Table II.
Dose Rates from Natural Radioactivity*

Source	Dose, mrad
External Irradiation	
Cosmic rays	28.7
Terrestrial radiation	50
Internal Radiation	
^{40}K	20
other radionuclides	1.6
Total	100

* estimated by UNSCEAR as average annual dose to gonads received by world population.

Table III.
Summary of Annual Whole-Body doses per Capita in the United States from Man-Made Sources*

Radiation Source	Dose, mrem
Medical	
Diagnostic	103
Therapeutic	6
Radiopharmaceutical	2
Occupational	0.8
Environmental	
Global fallout	4
Worldwide ^3H and ^{85}Kr	0.05
AEC installations	0.01
Nuclear power reactors	0.002
Fuel reprocessing	0.0008
Miscellaneous	2.6
Total	114
Natural	130

* estimated for year 1971 by the U.S. Environmental Protection Agency

Man-Made Sources of Radiation Exposure

The world-wide population dose from man-made radiation sources is still less than that incurred from natural radioactivity, although the background level is being approached in at least one industrialized nation. The average **per capita** dose in the United States is estimated for 1971 to be 114 mrem, compared to the average dose of 130 mrem/year from nature. Most exposure is received as a result of medical procedures for diagnosis and treatment of disease. Global contamination of the environment with radionuclides is primarily from atmospheric testing of nuclear weapons, but contributes negligibly to average **per capita** dose. Typical annual whole-body doses in the United States from various man-made sources **per capita** are summarized in Table III, where they are compared with that from nature.

Studies conducted by the US Public Health Service showed the main contributor of exposure in the medical arts to be diagnostic radiography. It is estimated that about 90 per cent of the total dose to the US population from man-made sources in 1971 was received from this source. Approximately 5 per cent resulted from irradiation for treatment of malignant and non-malignant diseases. Radioactive pharmaceuticals contributed less, and diagnostic dental radiography, negligibly.

Occupational exposure did not add appreciably to the total population dose. The portion of the United States population classified as radiation workers in 1969 was 0.4 per cent; the average radiation dose was 210 mrems/year. Most exposures higher than this were incurred by medical personnel.

External population exposure from fallout arises from radiations of environmental deposits, and internal exposures arise from contaminated food, water, and air passing through or absorbed by the body. Most of the dose is from strontium-90 (half-life of 28.5 years) incorporated in bone tissues. Additional exposure is from external irradiation by caesium-137 (half-life of 30 years), and, to a minor degree, from internal irradiation by several long-lived radionuclides, mainly carbon-14 (5730 years) and caesium-137. Atmospheric nuclear testing has now been reduced significantly hence fallout debris from recent and older tests has been diminishing.

Negligible population exposure in the United States resulted from radioactive releases from 13 operating nuclear power stations. The estimated average represents a very small fraction of the dose from natural or other man-made sources.

Operation of fuel reprocessing plants and USAEC facilities also resulted in minute exposure to the total population. Larger, but still small, doses are contributed from worldwide distribution of man-made tritium in surface water and krypton-85 in the atmosphere. Most of the tritium has arisen from previous atmospheric testing of nuclear weapons; smaller quantities are due to natural tritium and the amount from nuclear power reactors is a small fraction of the total.

Miscellaneous sources of radiation exposure include colour television sets, luminous watch dials, radiation gauges, static eliminators, and so on. These products contributed an average dose of 1.6 mrem/year. Transport of passengers and crews in aircraft adds 1 mrem/year to the average population dose, based on the average increase in dose equivalent rate from flight at an altitude of 9 kilometres of 0.7 mrem/hour. The average air crewman was estimated to receive 670 mrem/year.

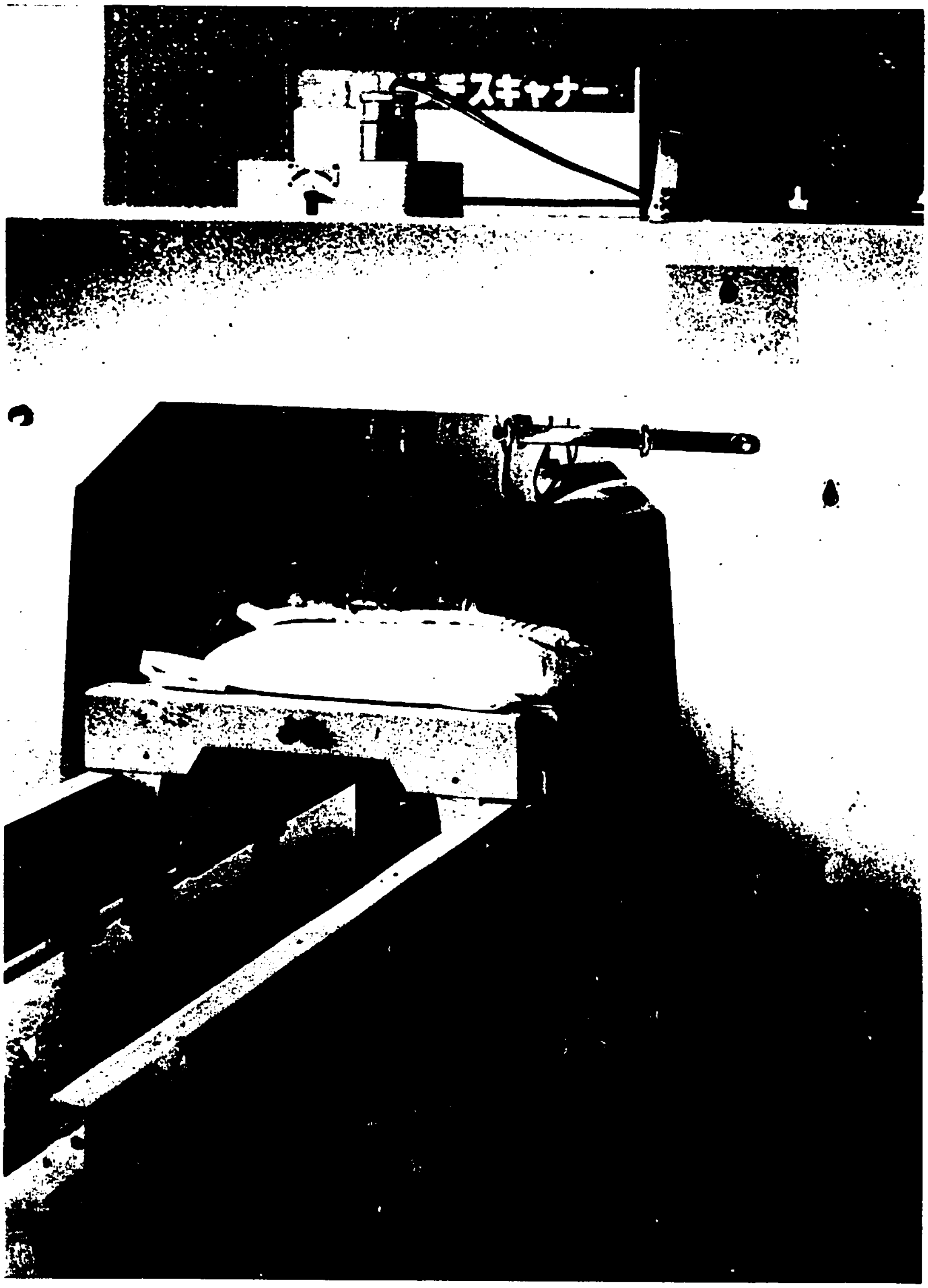
Doses from man-made radiation in other nations would appear to be contingent on local medical practices involving radiation and their rate of use by the public. Doses from other sources would not be expected to differ drastically since the major contributor is global fallout.

The average population dose in the United States in 1971 from nuclear power reactors and all other nuclear facilities is estimated to be 0.013 mrem. This represents 0.008 per cent of the genetic population dose limit of 5 mrems in 30 years. Other countries report similarly small contributions from nuclear power reactors. In the United Kingdom reactor operation at 11 sites in 1970 yielded an estimated dose of less than 0.003 mrem/year to the average individual. Monitoring at the site of 160-MW(e) gas cooled Tokai and the 330-MW(e) boiling water Tsuruga stations in Japan has shown no measurable addition to environmental radioactivity since operations commenced. Small but distinct increases above background radioactivity levels were reported from operation of the twin 200 MW(e) boiling water reactors at Tarapur, India, but concentrations were well below permissible levels.

The experience of many countries in the safe operation of a number of types of nuclear reactors has been most impressive and encouraging. Although there have been malfunctions of nuclear power reactors, in no case has there been release of radioactivity to the environment in amounts large enough to result in overexposure of the general public. However, from this limited experience, it cannot be assumed that the probability of release of large amounts of radioactivity to the environment as a consequence of an accident with a nuclear power reactor is zero. It is safe to assume perhaps that the probability of occurrence of major accidents is many orders of magnitude smaller than that of minor accidents, and major accidents will occur very, very infrequently and are not to be expected in the lifetime (approximately 30 years) of any given power reactor. A major accident is commonly considered to refer to one involving the release of thousands to a few hundred million curies of radioactivity to the environment. The probability of major accidents with modern nuclear power reactors of 1000 MW(e) or more is unknown, but guesses range from as low as 10^{-9} to as high as 10^{-4} accidents per reactor per year, depending on the severity of the accident. The consequences of an accident would depend, of course, not only on the amount of radioactivity released to the environment but upon many other factors: for example, the average age of the fission products, the type and quantity of fissile and transuranic elements present, the kind of release (i.e., to river, up the stack, release following meltdown and explosive rupture of the primary and leakage of the secondary containment), the meteorological conditions at the time (wind speed and direction, inversion conditions, rainout, particle size distribution), the population density in the neighbourhood of the plant and the rapidity and efficiency with which remedial measures are taken (e g., the implementation of a well-though-out and frequently rehearsed emergency procedure that provides safe and rapid relocation of the potentially exposed population and proper care of injured).

Several attempts have been made to determine the consequences of releases of substantial amounts of the radioactive products in a reactor accident. Under adverse but possible meteorological conditions and with an emergency system and an early implemented evacuation procedure meeting the minimum requirements of a good public health program, it would seem that even with 25% release of the iodine isotopes and 100% release of the noble gases (or a few hundred million curies) from a 1000 MW(e) power reactor, the exposure to a typical population in a metropolitan area would be maintained at less than 2.5×10^6 man-rems of total body dose and 30×10^6 man-rems thyroid dose. If one applied the conservative assumption that there is a completely linear relationship between this dose and the number of fatal malignancies, life

A Japanese being examined under a Scintiscanner, which may be used to delineate the uptake of radioisotopes within the body as a part of diagnostic procedures.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shortening death equivalents, and first generation genetic deaths and applied the coefficients of ICRP, this hypothetical worst case design (credible) accident would account for something less than 500 deaths. This number would include both the delayed deaths when applying the linear hypothesis and the few prompt deaths from "radiation sickness" of those receiving large exposures of greater than about 500 rem. The probability of such an accident is considered to be extremely small because of the engineered safety features that are applied.

At the lower end of the scale of major accidents, a few thousand curies (rather than a few hundred million curies) of radioactive material released to the environment would be expected to contribute a total body dose of only about 25 man-rems and, on the same linear hypothesis, this would result in no radiation deaths.

If one very conservatively assumes that the most severe accidents would occur at a frequency of 10^{-5} accidents per reactor year they might contribute, in a system of 500 operating nuclear power plants, up to two to three deaths per year. These risks can be compared, for example, with a hundred deaths per year in the United States of people struck by lightning (88 in 1967 and 129 in 1968). The risks are very small set against the number of deaths in a typical year resulting from accidents in air transportation in the United States (1799 in 1967 and 1904 in 1968). Psychological and public acceptance factors need to be taken into consideration, however, when considering possible nuclear accidents. How would the public react to a major reactor accident every twenty or thirty years? and what will be its consequences on the reactor programme? There is a popular tendency to accept familiar hazards while reacting violently to unfamiliar ones, such as radiation and nuclear contamination. The public is aware that radiation protection standards are established on the assumptions, which at present can be neither proved nor disproved, that there may be genetic as well as somatic effects from radiation, that effects are cumulative and irreversible and that there is no threshold level below which effects do not occur. This is felt to be a conservative approach but it is prudent to recognise the possibility of major accidents, however remote, and to undertake public health measures to educate the public, to assure and convince the public that proper care has been taken to protect them by building a safe reactor, caring for its good siting, ensuring its safe operation, being prepared to minimize the effects of possible accidents, and undertaking a programme to improve power reactors and their operations continually, thus reducing further the probability of accidents and profiting from experience with minor accidents.

safe handling of radioactive materials

Introduction

Fission within nuclear fuel creates radioactive substances with a wide variety of chemical, biological and radiological characteristics. The safety of both plant personnel and the public in the vicinity of nuclear power plants depends to a very great extent on the containment of these products within the fuel, where they are formed for the most part. In normal operation very small quantities of fission products are released from the fuel through defects in fuel cladding. Management of these generally imposes no unusual constraints on facility siting, which depends largely upon considerations of accident potential and consequences.

Exposure of the public to ionizing radiation due to radioactive effluents from nuclear power plants can be kept at small fractions of the levels set in radiation protection standards for routine operations, but it is recognised nevertheless that nuclear power productions is but one part of the fuel cycle. In order to examine fully the overall impact of the use of nuclear fuel for electrical power generation one needs to consider the whole fuel cycle, beginning with mining and milling and ending with the final disposal of wastes from the operations carried out at various stages. However, reactors are of major interest to most members of the public because there are more of them than of other facilities in the fuel cycle, and they are sited generally closer to electricity load centres – broadly, people in towns.

When considering the effective management (control) of radioactive effluents from reactors and associated facilities one does well to keep in mind that everything, including effluents from all power plants, whether they use fossil or nuclear fuels, contains some radioactive material. The management of radioactive wastes is concerned not so much with reducing levels of contamination to zero or even to the lowest possible level, as with keeping the total addition of radioactivity to the environment as low as is practicable – in any case, within the limits recommended by ICRP.

The contamination of air by nuclear power plants is predominantly by radioactive noble gases, which do not concentrate in the body but are responsible primarily for external radiation exposure. In order to assure adequate radiation protection for members of the public the concentration of radioactive materials in air, water and food as a consequence of reactor operations and ancillary activities must be kept at such a low level that the total risks of somatic and genetic injury are exceedingly low, no greater than risks introduced by other common industries. These risks must be acceptable by the individual and by the society of which he is a part.

Whenever practicable, radioactive materials are concentrated and contained in isolation from man's environment until their radioactivity has decayed to innocuous levels. When release to the environment is necessary the rates of release must be low enough not to exceed the local capacity of the environment to disperse and dilute the materials to acceptably low concentrations. In this respect the environmental processes that may lead to reconcentration and may provide a pathway for man's exposure to additional radiation must be considered.

Radioactive effluents released from nuclear power plants are always monitored as a means of control and public protection. Additional, off-site monitoring is carried out as a confirmatory means of environmental protection, but in general releases have been so low that little indication can be found of radiation above natural background levels.

The installations associated with other aspects of the nuclear fuel cycle are fewer in number and generally more remote from large centres of population than reactors, but effective management of radioactive materials to control both occupational and public exposure to ionizing radiation is still required. In mining and milling operations on uranium and thorium ores required for nuclear fuel fabrication the principal problems arise in occupational exposures, particularly through the inhalation of radon gas and the radon daughter products. In first cycle enrichment operations waste management involves the effective control of naturally-occurring heavy elements. However, when spent fuel is reprocessed for recovery of unburned uranium the recovered product contains plutonium, which is also valuable as a fuel.
The uranium recovered is returned to enrichment plants for re-enrichment.
Fuel fabrication operations also require effective management of these same elements.
In general, the provision of clean working conditions for operating personnel and the strict accountability of the fuel materials contribute to the control of these materials.

Well over 99.9% of all the radioactivity generated in nuclear power reactors is contained within the fuel elements until they are reprocessed for recovery of unburned fuel. Thus careful control of the inventories in reactors and of the spent fuel which must be handled and transported to fuel reprocessing plants is required.
A reprocessing plant may accommodate the spent fuel elements from several power reactors, and it is during the reprocessing of the fuel that high-activity wastes are generated. These wastes must be kept in containment for very long periods of time, ranging from a few centuries to possibly thousands of years, if they contain substantial concentrations of transuranic elements. Although storage as liquids in tanks near the ground surface has been a suitable and reliable method for containment of these wastes to date processes of solidification have been developed, and some countries have already decided that such wastes will be solidified to reduce the potential "environmental mobility" of these wastes during long periods of time. Consideration is also being given to various means of storage of these wastes, including their storage in deep, dry and stable geologic formations in order to assure further their isolation from the human environment for the time required.

Mining, Milling, Enrichment and Fuel Fabrication

The mining of uranium ores is the starting point in the production of fuel for nuclear power plants. These ores contain oxides of uranium in relatively low concentrations, mixed or combined with other minerals and rocks. The radioisotopes associated with the uranium ores are naturally-occurring decay products of uranium, thorium and radium.

Mining gives rise to two types of waste, airborne dust with some radon, and solid tailings containing some uranium oxides and a very small quantity of radium. The concentration of radon is controlled by the volume of air used in ventilation. When airborne dusts are a problem the air may be filtered and in special cases, if necessary, the miners may use respirators to limit their exposure to radiation.

The next step in preparing the uranium oxide for use in fuel fabrication is the milling and concentration of the oxide. The uranium-bearing ores are crushed into a relatively fine form (like sand of fine texture) in preparation for leaching of the uranium. Since the uranium is only a small fraction — generally less than 1% — of this material the bulk of it remains as tailings for disposal as both solid and slime-like wastes. The quantities of uranium oxides and of radium sulphate in these wastes are limited purposely since they are intrinsically valuable and must be accounted for; they occur usually in a finely-divided state, and wet. The radioactivity of the uranium is not a controlling factor at this stage — much more important is its chemical toxicity. The solid and slime-like wastes are often deposited on a tailings pile where leaching of radium and escape of radon can occur. Recent trends are toward drying these wastes and storing them in dry mines or incorporating them in bitumen, thus isolating them from the environment. The airborne wastes, again, are treated by filtration and the use of adequate ventilation. The nature of the operations here permits a close control of the airborne materials.

Thorium is not used at present as a fuel for power reactors, and its mining and milling has not yet become an important source of radioactive wastes. This situation could change in the future.

The uranium oxide is commonly converted next into uranium hexafluoride (UF_6), which can be maintained in a gaseous state. In this form the uranium may be enriched in a gaseous diffusion

An open pit uranium mine in New Mexico. The spiral dump is of waste. Photo: USAEC

plant in any of a number of countries; enrichment is necessary to increase the proportion of thermally fissionable ^{235}U to non-thermally fissionable ^{238}U from the natural abundance of about 0.7% to about 2.2 – 3%, to make it more suitable for use in the most common types of power reactors. Unburned uranium from the reprocessing of spent power reactor fuels may also be recycled through the enrichment plants. Gaseous wastes are filtered prior to release to the environment.

After enrichment the uranium hexafluoride is converted again to an oxide or to the metal for use in the fabrication of reactor fuel elements. Fuel fabrication gives rise to various types of liquid, gaseous and solid wastes which are slightly contaminated with uranium, its daughter products and plutonium (when recycled materials are used).

Nuclear Power Plants

Sources of radioactivity

Both nuclear and conventional power plants use much the same type of machinery to convert steam to electricity, and to connect this to the electrical grid. The uniqueness of the nuclear plant lies in the fuel used, and more particularly in the equipment needed to maintain strict control over the radioactive materials formed by the fission process that generates heat.

. . . Fission products

The principal radioactive materials formed are the fission products. The quantity of fission products formed is small in terms of mass: in a large power plant this will amount to only a few kilograms each day. Since some of the fission products decay as others are formed the amount of radioactivity levels off and the inventory of short-lived fission products reaches essentially a steady value. Because the shorter-lived radionuclides contribute substantially to the total inventory of radioactivity in terms of curies after a few weeks of operation of a light-water moderated power reactor using fuel slightly enriched in ^{235}U the fission product inventory might be up to about 40% of what would exist after a two-year operating period. More importantly, as will be explained later, all but a very small fraction of the radioactive fission products remain confined within the fuel element where they were formed. The quantity of fission products within reactor fuel elements will depend upon:

- average operating power level of the reactor
- fuel residence time in the core
- time elapsed for radioactive decay.

. . . Activation products

Structural materials used in the reactor and the components which remove the heat from its core will corrode and erode only very slightly with time – but enough to create fine particulates identified broadly as "corrosion products". These corrosion products, along with other impurities in the coolant, circulate through the core of the reactor, where they are exposed to neutrons. Neutron bombardment causes them to become radioactive. The quantities of radioactive materials so formed are small compared with the fission products, and consist commonly of radioisotopes of elements such as iron, cobalt and manganese. Some reactors use boron in the reactor core and core coolant to control the fission process. Neutron absorption by boron leads to the formation of tritium, a radioactive isotope of hydrogen. Tritium formation similarly can result where water is used as the core coolant, through conversion of deuterium – a natural isotope of hydrogen found in water. In gas-cooled reactors, cooled with carbon dioxide, the activation products include ^{41}A and ^{14}C.

Radioactive waste generation and management

Although the kinds of radioactive wastes produced as by-products of the fission process are basically the same for all uranium fuelled reactors the characteristics of the effluents from plants can vary appreciably, depending on the reactor coolant and steam cycles used. The radioisotopes in the effluent streams in turn influence strongly the design of particular waste treatment systems.

Objectives in plant design are so to process and recycle waste streams as to minimize both volume and radioactivity of effluent wherever practical. Releases to the environment are controlled both by batch processing of effluents, and/or by continuous monitoring before discharge to ensure that no release exceeds established permissible limits.

The waste management techniques now in use for **gaseous wastes** are delay and decay; filtration; and low temperature adsorption on charcoal. Delay and decay refer to the storage of waste for long enough to decrease the associated treatment problem by permitting some radioactivity to decay before release. The usefulness or efficacy of this technique as a means for reducing activity levels in gaseous wastes depends on the particular isotopes present. Gases are then filtered and released through stacks to the atmosphere. Filters collect radioactive solid particles formed when a gaseous parent nuclide decays to a particulate radioactive daughter, or become attached to particles; and when particles of dust are carried by the air stream through the reactor core. Specially-treated charcoal filter beds may be used to remove iodine. Low temperature adsorption may be useful in providing delay and decay of short-lived noble gases.

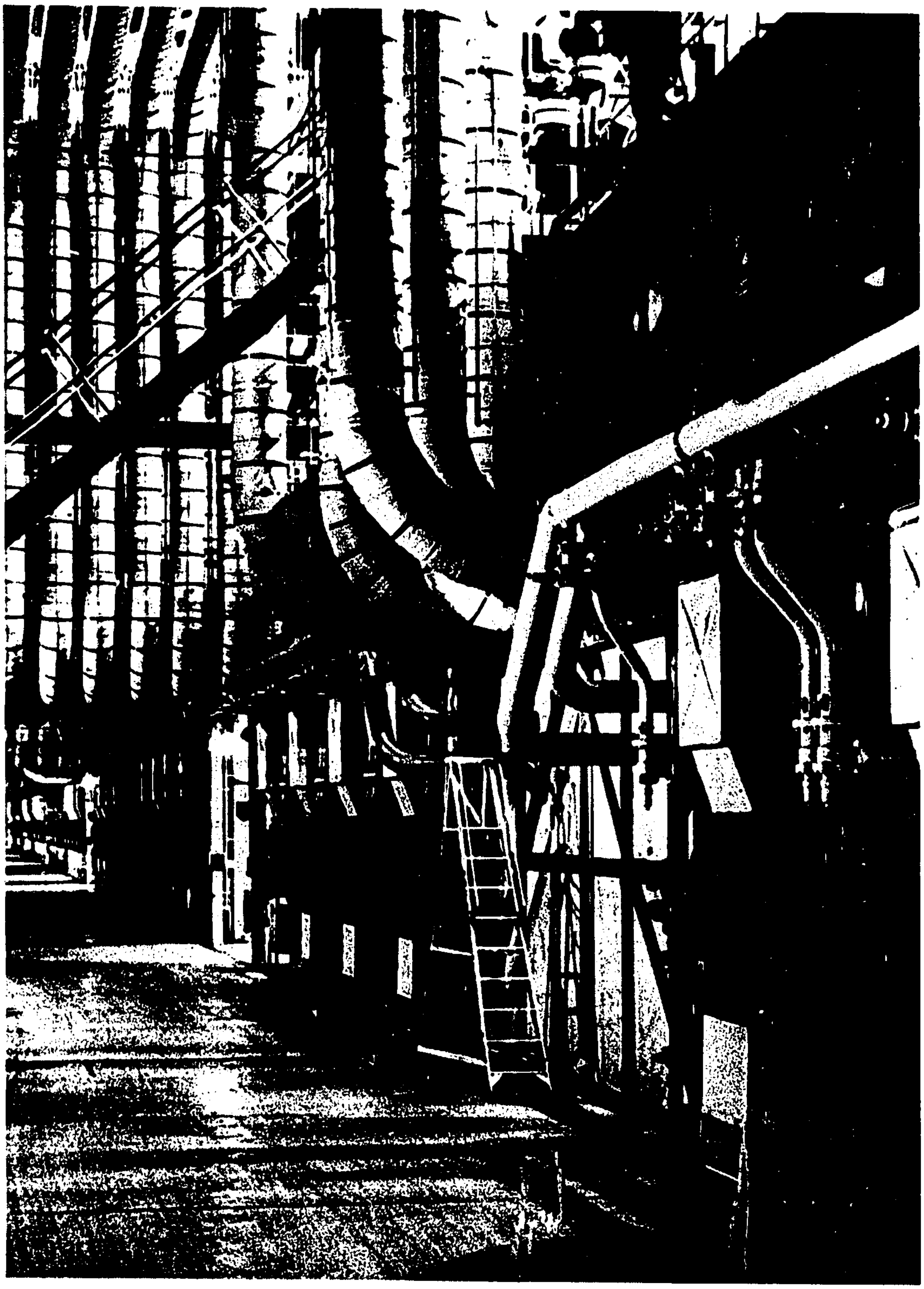
Liquid waste management systems employ four basic treatment techniques to reduce levels of radioactivity. These are delay and decay; filtration; evaporation; and demineralization. In the case of reactors in which once-through cooling systems are used a final reduction in liquid radionuclide concentrations is achieved by dilution of the wastes in the condenser cooling water to ensure that radionuclide concentrations are at the lowest possible level before reaching the site boundary.

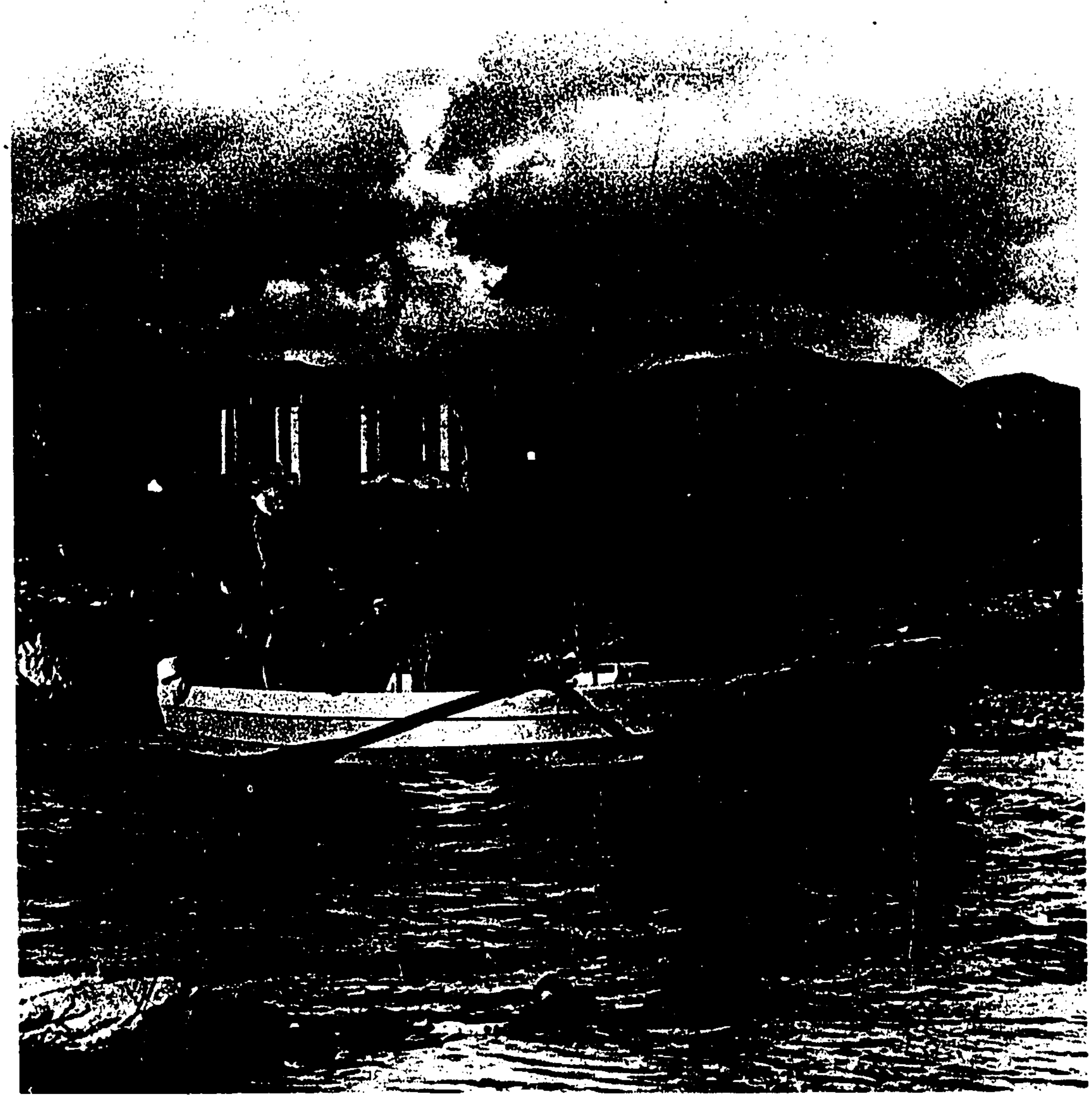
The **delay and decay** technique as used in the treatment of liquid waste is identical in principle to that for gaseous waste, although little reduction in liquid radioactivity levels is achieved. Radionuclides in liquid radioactive wastes tend to have relatively long half-lives since those with shorter half-lives decay during their movement through the plant. A relatively long delay time would be needed to achieve any appreciable reduction in liquid waste radioactivity levles – it is estimated that it would take about 40 days to reduce the radioactivity levels of typical liquid waste by a factor of about five.

Filtration is commonly used for treatment of waste streams containing primarily insoluble or particulate contaminants. Filtration is also frequently employed with other types of waste treatment as a pre- or post-treatment step for the process liquid. In pre-treatment filtration the objective is removal of suspended solids to prevent interference by particulates in the subsequent treatment processes. In post-treatment application, filters are used for tasks such as the collection of resin "fines" escaping from ion exchangers. Filter types used include natural filtration (using sand or other media), activated carbon, vacuum and pressure pre-coat type filtration and fibrous and knife-edge filtration.

Evaporation separates water from non-volatile dissolved and insoluble radioactive wastes by boiling. This concentrates and reduces the volume of the contained wastes and reduces the activity level of the effluent, permitting easier ultimate disposal. The efficiency of this technique for radioactive waste treatment can vary

Part of the interior of the gaseous diffusion uranium enrichment plant at Capenhurst, in the UK. Photo: UKAEA





widely depending on the radioactive materials present. A reduction of 100 to 1000 in the activity level can be achieved, depending on the mass velocity of the vapour in the evaporator and decontamination efficiency for non-volatile radioactive contaminants. If volatile radioactive materials such as tritium, iodine or ruthenium are present the overall reduction in activity level may be substantially less on account of carry-over of these materials. Evaporation is a common method of treatment of liquid wastes because streams having a relatively high content of dissolved solids can be accommodated. It is, consequently, a suitable process for use in conjunction with subsequent ion-exchange treatment. Care needs to be taken, however, to provide for treatment of any feed streams, such as laundry wastes which contain organic agents.

The efficiency of demineralizers (ion-exchange resins) in the treatment of waste streams depends on the type, composition and concentration of waste liquid, the type of exchange, regeneration methods, radionuclides present and operating procedures. The reduction in activity levels achieved may be as low as 2 and as high as 10^5. Only wastes containing relatively small amounts of dissolved and suspended solids can be processed efficiently by ion exchange because bed exhaustion occurs rapidly for liquids with a high total content of dissolved solids. Suspended solids will clog an ion exchanger and also prevent its efficient operation. Thus, the use of ion-exchange treatment is restricted to radioactive wastes with low total dissolved solids and low suspended solids, and filtration is always used as a pre-treatment.

Boiling Water Reactors

Boiling water reactors (BWRs) are one of the two types of light water reactors which are being operated and marketed on a wide scale at present. In a BWR water is circulated through the core of the reactor, where it is converted under pressure into steam (See Fig.6). This high-temperature stream is used to drive a turbine to generate electricity, and is then cooled in a condenser and recirculated through the reactor core. Water is used to cool the condenser. The basic operation of such a plant, apart from the nature of the fuel, is similar to that of a fossil-fuelled installation. (See Fig.7)

BWR Waste Management Systems

More than 99% of the radioactive gaseous effluents from boiling water reactors are removed continuously with relatively large volumes of air through the condenser air ejector. Additions to the gaseous emission come via the condenser gland seal, primary containment air, gases from the radiochemical laboratory at the plant, the radwaste [radioactive waste] treatment area, laundry, decontamination operations and various tank vents. The gaseous waste contains primarily the activation product ^{13}N, isotopes of the noble-gas fission products krypton and xenon, and tritium. About 90% of the ^{13}N decays to a non-radioactive isotope in the time it takes for the gaseous waste to be transferred through the plant to the stack and from there to the site boundary. Consequently, it is of minimal concern in offsite areas. The isotopic composition of the krypton and xenon depends on the radiation history of the reactor fuel and on the age of the mixture at the time of release, because many isotopes of krypton and xenon have a relatively short half-life. Some radioactive particulates appear in the gaseous waste as a result of entrainment and decay of noble-gas precursors; isotopes of some of the more volatile elements, such as iodines, will be carried over as vapour.

A typical operating BWR off-gas system is shown in Figure 8. Non-condensible gases are drawn from the main condenser through steam jet air ejectors and condensers into a delay line, where they are retained for 30 minutes or more, depending upon design requirements. After this delay time the gases pass through an absolute particulate filter and are discharged through the stack. The stack is usually about 300 feet high, although its actual height is influenced by site topography. Since a major portion of the activity released from a BWR is composed of short-lived gases, an elevated release (as opposed to a ground-level release) contributes to effective dispersal and decay. Off-gases from the turbine gland seals are processed similarly. Because these are mainly short-lived activation gases and the volumetric flow rate is very large, only a two-minute delay is commonly allowed for before they are discharged through the stack.

Provisions can be made in the design of BWRs to reduce greatly the discharge of short-lived noble gases. This can be accomplished through the use of activated charcoal beds to delay the noble gases for a time long enough to permit additional radioactive decay. This would have little influence on releases of ^{85}Kr at the reactor site since this radionuclide has a half-life of about ten years, but its contribution to radiation doses in the vicinity of the plant is negligible. Like all other fission products, practically all of the ^{85}Kr formed is retained in

Fly-fishing trials taking place on the lake at the Trawsfynydd nuclear power station, Wales. Photo: Central Electricity Generating Board.

the fuel elements until they are processed for recovery of plutonium and unburned uranium.

A typical BWR liquid radwaste processing system is shown in Figure 9. The unique feature of this system is in the segregation of wastes by chemical and physical properties. Influent is collected and processed according to its classification as high-purity (equipment drains), low-purity (floor drains), chemical, or laundry wastes. Contents of equipment drains are filtered and demineralized, and can then be either used again in the plant, or measured and discharged. Plant floor drains, chemical wastes and laundry wastes are filtered and discharged from the plant. Since the laundry wastes tend to foul filtering media, they are processed separately through their own filter.

The major sources of solid radioactive wastes at BWRs are sludges which accumulate on filters, and demineralizer resins. These wastes are first centrifuged to remove excess water then solidified with concrete in 55 gallon (0.2 m^3) steel drums. The drums are normally stored for three to six months before shipped offsite for permanent burial. About 100 – 175 drums are shipped each year from a typical BWR installation.

BWR Operating Experience

A radiological surveillance study was performed in the United States at an operating BWR power station. In this study the characteristics of the gaseous effluent discharged to the environment were measured: the average fission-product noble-gas release rate was 12 500 μCi/sec while the plant was operating, which was during 64% of the year. The principal radioactive noble gases found in the laboratory effluent analyses were ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, and ^{138}Xe. One day after release only ^{88}Kr, ^{133m}Xe and ^{135}Xe were detected in the sample; after one month the only noble gases detectable were ^{133}Xe and ^{85}Kr. Tritium could also be detected in the laboratory sample. The principal non-noble gas fission product found was ^{131}I.

Data for gaseous releases of radionuclides to the atmosphere from ten BWRs operating in several countries are shown in Table IV.

The constituents of radioactive liquid waste from a BWR are activated corrosion products, and fission products. The fission product levels are attributable to tramp uranium*, and to

* "Tramp" uranium refers to the tracers of uranium that may be found on the outer surfaces of the fuel cladding.

Figure 6: Schematic diagram of a typical boiling-water reactor

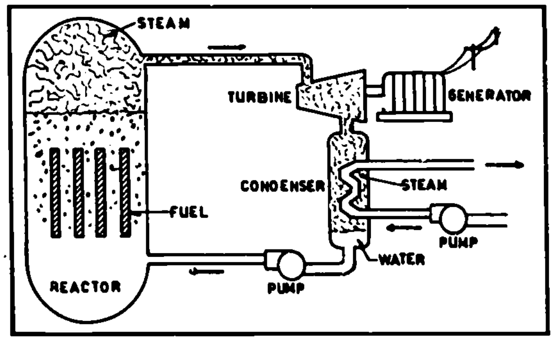


Figure 7: Schematic diagram of a fossil-fuelled generating plant

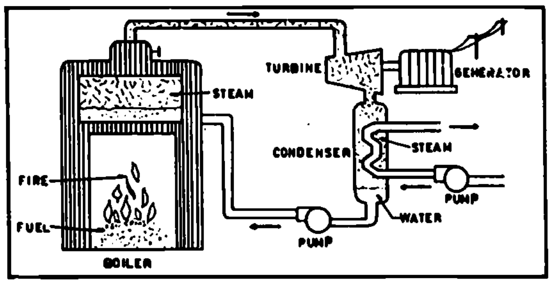


Figure 8: Typical BWR off-gas system

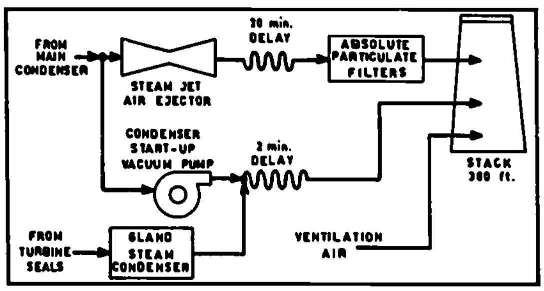


Figure 9: Typical BWR liquid radioactive waste system

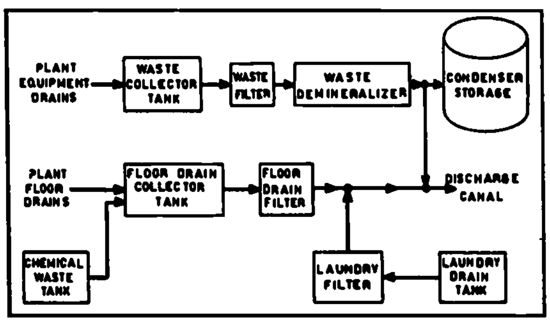


Figure 10: Schematic diagram of a typical pressurized-water reactor

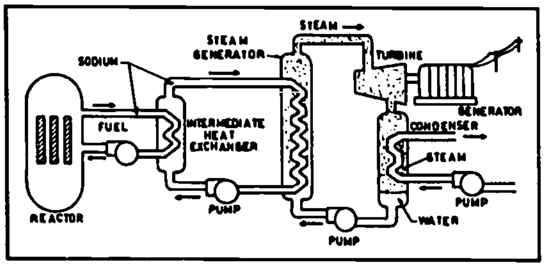


Figure 11: Typical PWR gaseous waste system

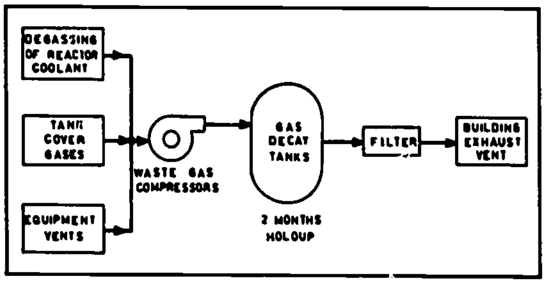


Figure 12: Typical PWR liquid radioactive waste system – dirty wastes

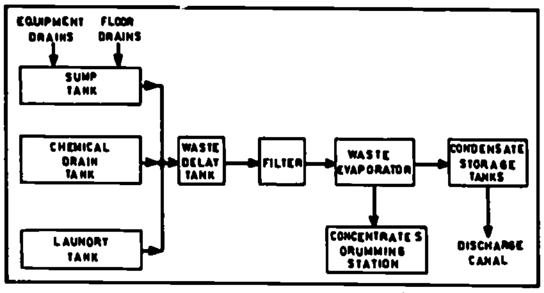
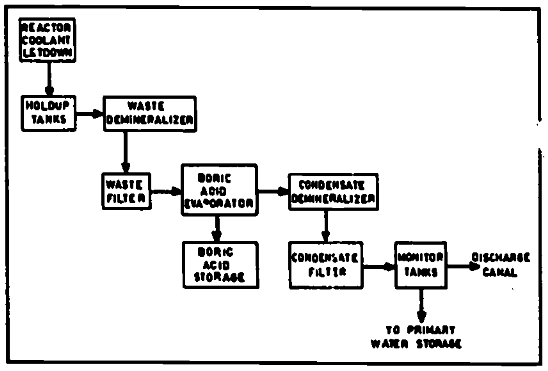


Figure 13: Typical PWR liquid radioactive waste system – clean wastes



leakage from fuel elements through cladding defects. The relative contribution of leaking fuel elements depends, of course, directly upon the number of leaking fuel rods and the severity of the leaks.

The characteristics of the liquid waste effluent were also measured in the study mentioned. The average concentration of all detected soluble and insoluble radionuclides in the waste prior to dilution was approximately 2×10^{-3} μCi/ml. The radioactive constituents at the highest concentrations were ^{3}H, ^{58}Co, ^{89}Sr, ^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs, ^{140}Ba and ^{144}Ce. The average contribution to the total unidentified activity in the water used for radioactive waste dilution was 0.189×10^{-7} μCi/ml over a one-year period. This may be compared with the ICRP recommendation for the maximum permissible concentration of unidentified radionuclides in water, (MPCU)w, of 10^{-7} μCi/ml if neither ^{226}Ra nor ^{228}Ra is present. The study concluded that exposure to the surrounding population through consumption of food and water was not measurable.

Pressurized Water Reactors

The second type of light water reactor in common use is the pressurized water reactor (PWR). Pressurized water reactors operate under pressure high enough to ensure that the water passing through the reactors does not boil. This water passes through a steam generator to make steam to drive the turbine (Fig.10). The water in the primary coolant system does not mix with the steam used to drive the turbine.

PWR Waste Management System

Since the primary coolant in pressurized water reactors does not boil most of the gases are contained within the primary coolant system. Gases which do leave the primary coolant system are collected and routed to storage tanks. The general composition of the gaseous waste produced in a PWR is somewhat different from that produced in a BWR. Since PWR gases remain in the plant for a longer time before discharge the shorter half-life isotopes are much less abundant in the gaseous waste of a PWR than in that of a BWR. Occasionally, primary coolant leaks into the secondary system through defective steam-generator tubes. When this occurs short-lived gaseous radioactive wastes may be released through the main condenser air ejector.

A typical PWR gaseous radwaste system is shown in Fig.11. The waste gases from various

Table IV.
Operating Experience of Releases of Gaseous Radionuclides to the Atmosphere from Boiling Water Reactors in 1970

Plant	Nominal Rating (MW(e))	Gross Electrical Generation (10^6 MWh)	Annual Average Emission Rate (μCi/sec)
Dresden 1	200	1.50	30,000
Big Rock Point	72	0.38	9,000
Humboldt Bay	70	0.43	16,000
Garigliano	150	0.74	16,000
KRB	237	1.84	1,000
Tarapur (2 units)	380	2.17	14,000
Oyster Creek	640	3.56	3,500
Nine Mile Point	600	1.63	< 1,000
Tsuruga	342	1.89	1,800
Dresden 2	809	1.25	8,600

sources are collected in a vent header and discharged by a waste-gas compressor into one of several decay tanks. When a tank reaches a set pressure and activity level it is isolated and a second tank is placed in service. Gas is held for decay for from one to two months before being discharged through a filter to the environment from a building vent. Since these gaseous wastes are small in quantity and contain minimal activity dispersal from an elevated stack is not necessary.

A typical PWR liquid radwaste system is shown in Fig. 12 and Fig. 13. Dirty wastes from various sources (Fig.12) are collected in separate tanks and, when ready for processing, are discharged to the waste-holdup tank. This tank serves primarily as a batching tank for the waste evaporator. The distillate from the evaporation process is condensed and stored in a condensate storage tank before discharge from the plant. The concentrates are collected and stored for processing through the solid radwaste system.

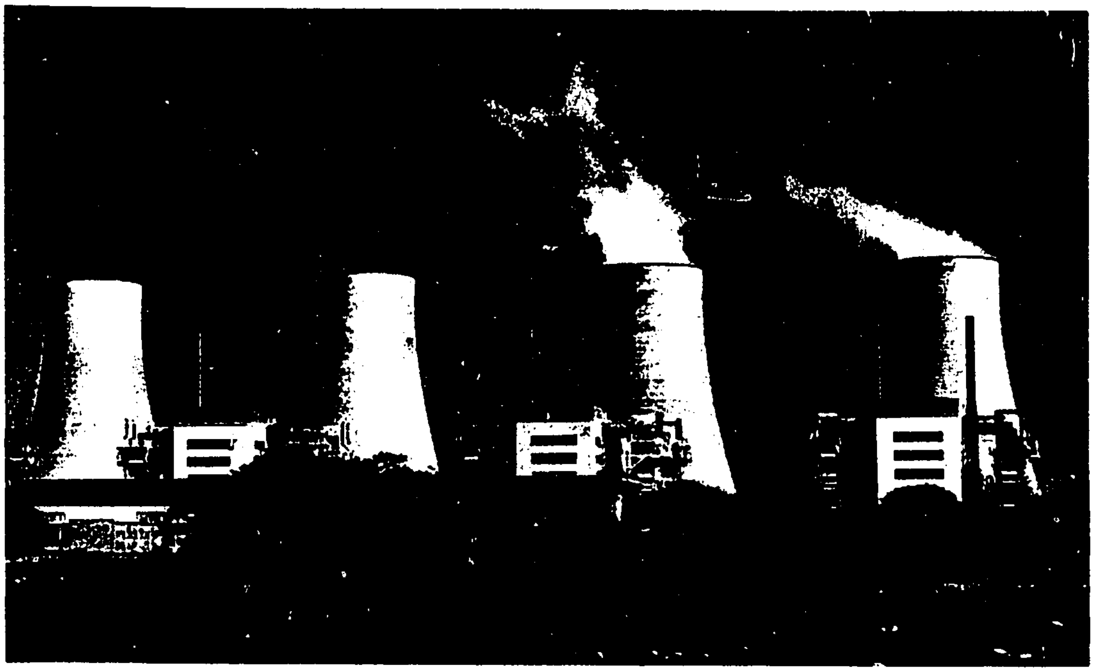
Clean wastes (Fig.13), which consist primarily of reactor coolant, are collected in holdup tanks. After filtration and demineralization of these wastes the boric acid evaporator serves primarily to recover boric acid and primary grade water. The boric acid evaporator condensate, after being filtered and demineralized, can be recycled to the primary coolant make-up tank or measured and released to the discharge canal.

Solid radioactive wastes from a PWR may be processed differently depending upon the source, the activity and the choice made by the plant operator. Evaporator concentrates are solidifed with a mixture of cement and vermiculite in 55-gallon (0.2 m^3) steel drums.

PWRs use cartridge-type filters that consist of paper or fibre elements held in a steel cage. Usually only the elements need changing, but occasionally the entire cage assembly must be replaced. In either case, the component to be disposed of is placed inside a 55-gallon (0.2 m^3) steel drum lined with cement for shielding purposes. More cement is added to encapsulate the component completely. The drum is then capped. All processed solid radwaste is stored on-site before being shipped to a burial ground for final disposal. These shipmants range form 100 – 175 drums a year.

PWR Operating Experience

A recent radiological surveillance study performed in the US at an operating PWR power station measured the characteristics of the gaseous wastes at several points in the waste management systems. The maximum annual gross beta-gamma level of activity discharged in gaseous effluents was approximately 22 curies



The Chapelcross nuclear power station, in Dumfriesshire, Scotland. Photo: UKAEA

for the year 1962 and averaged 5.3 Ci/year between 1962 and 1968. The radionuclides found in the gaseous waste were ^{3}H, ^{14}C, ^{85}Kr, ^{133}Xe and ^{135}Xe. No gaseous ^{131}I was found at the minimum detectable level. Based on measured concentrations in the surge drum and subsequent dilution, four radionuclides were estimated to be present at the site boundary in concentrations corresponding to 0.002%, 1.0%, 0.03% and 0.01% respectively of their individual maximum permissible concentrations. Concentrations at the site boundary were conservatively estimated to be 0.01% of the limit for ^{90}Sr. Secondary sources of gaseous waste such as the condenser air ejector and secondary system liquid waste-tank vents appear to be the major contributors to effluent radioacitvity: for example, all but one of the recorded gaseous tritium discharges occurred during months when the vapour container was vented or gas was released under special circumstances.

Liquid wastes from PWRs are similar to those from BWRs except that tritium is a much more significant constituent. This abundance of tritium arises mainly from diffusion of the fission-produced nuclide through stainless steel clad fuel and from extensive use of boron and lithium in PWR coolants. The boron undergoes a neutron-capture reaction with the fission neutrons — generating tritium, which has a relatively long half-life of 12.3 years and which combines with oxygen to form water. Tritiated water is chemically identical with ordinary water, making its separation and removal extremely difficult and, to date, impractical.

Diffusion of fission-product tritium into the primary coolant can be reduced by changing from stainless steel cladding to zirconium cladding, which reduces leakage from about 30% of the fission-product tritium to 1%. The tritium in the primary coolant, including that produced by activation of boron and lithium, would not be removed regularly but would be recirculated. If it became necessary to replace the primary coolant during the lifetime of the reactor special provisions could be made for its handling.

Reactor coolant contributes to the PWR liquid waste through expansion overflow, reactor letdown flow, component leakage and sampling. Other sources of liquid waste include floor drains, decontamination and laundry wastes.

The characteristics of PWR liquid radioactive wastes were also reviewed in the study mentioned. After release, aside from low concentrations of radionuclides found in sediment and vegetation near the point of discharge, the

Table V.
Operating Experience of Radionuclide Releases from Pressurized Water Reactors

Plant	Year	Total Liquid Released (Curies)	Total Gases Released (Curies)	Total Tritium Released (Curies)	Fuel Clad Material
Yankee (625 MW(t))	1967	0.055	2.3	1690	Stainless Steel
	1968	0.008	0.68	1170	Stainless Steel
	1969	0.019	4.14	1225	Stainless Steel
	1970	0.036	16.5	1375	Stainless Steel
Conn. Yankee (825 MW(t))	1968	3.96	3.74	1740	Stainless Steel
	1969	12.2	190.0	5100	Stainless Steel
	1970	29.5	876.0	7376	Stainless Steel
San Onofre (1345 MW(t))	1969	8.90	251.0	3500	Stainless Steel
	1970	3.80	1606.0	4769	Stainless Steel
RG and E (1520 MW(t))	1970	9.35	9974.0	107	Zirconium

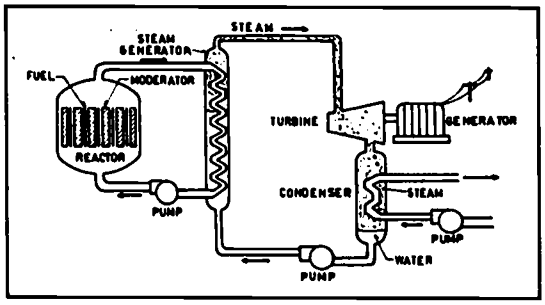
only measurable radionuclide in water was tritium. Other major radioisotopes in the released waste were ^{14}C, ^{51}Cr, and ^{58}Co. Lesser amounts of ^{32}P, ^{54}Mn, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{110m}Ag, ^{124}Sb, ^{131}I and ^{137}Cs were also discharged. Data on the discharge of radioactive wastes from four operating PWRs are shown in Table V.

Gas-Cooled Reactors

The extensive use of gas-cooled reactors as the basis for a nuclear power programme has been confined to the United Kingdom and to France. The type of gas-cooled reactor which has been operated for power production so far is the natural uranium fuelled, graphite moderated, carbon dioxide cooled reactor. In the UK about 85% of the total installed nuclear capacity of more than 5000 MW(e) is operated by the Central Electricity Generating Board (CEGB); in France about 94% of the installed nuclear capacity of more than 1300 MW(e) is operated by Electricité de France (EDF). More advanced gas-cooled reactor systems are in the prototype stage.

A schematic diagram of a typical gas-cooled power reactor is shown in Fig.14. The fission process takes place in natural uranium rods which are sealed in finned magnesium alloy cans. The fuel elements are arranged in vertical fuel channels, each containing about eight elements. There are several thousand such fuel channels together with channels for control and safety rods in the reactor core, basically a graphite block about 10 m high and 13 m in diameter. The core is contained in a pressure vessel of either steel or pre-stressed concrete. The carbon dioxide coolant is circulated through the fuel channels, where it removes heat from the fuel, and then through a steam generator. While passing through the core the coolant gas is activated by neutrons and it also becomes contaminated with particulate erosion products of activated reactor components. Deliberate discharges of coolant gas from the reactors takes place from time to time — for example, to maintain correct pressure or coolant or coolant purity — and some leakage from the coolant circuit also takes place. Thus the activated materials in the carbon dioxide con-

Figure 14: Schematic diagram of a typical gas-cooled reactor



stitute a source of gaseous and particulate radioactive release to the atmosphere. In steel pressure vessel reactors the pressure vessel is surrounded by a concrete "biological shield", and air is blown through the annular space between the two. The main purpose of this air is to cool the concrete of the shield, but it also sweeps over many of the potential points of leakage from the pressure circuit and caries entrained waste to the atmosphere above the reactor roof. Constituents of the shield cooling air itself, and particulate matter carried by it, are activated while passing close to the pressure vessel.

Gas-Cooled Reactor Management Practices

The experience of the UK and France has been that the arrangements provided in the design of power stations for dealing with radioactive wastes have proved adequate to keep discharges to the environment within limits imposed by the national authorizing organizations, and in accordance with the conditions laid down by these authorities.

As is implied in the previous paragraph, measurements are made on discharges of radioactive waste. There has been no requirement for the regular measurement of gaseous discharges from CEGB nuclear power stations, since these are dependent largely on reactor power and are calculable. In practice, radioactivity from gaseous wastes has proved difficult to detect in the environment. Particulate radioactive gasborne materials are monitored during discharge from the principal points of release. At the Electricité de France power stations, at Chinon and St. Laurent des Eaux, both gaseous and particulate activities are measured routinely. Liquid wastes are monitored before discharge while being held in final monitoring and delay tanks.

Gaseous wastes originate largely from the planned release of reactor coolant gas, and the discharge of air used to cool the concrete shield in steel pressure vessel reactors and to ventilate the buildings containing the reactors and ancillary plant. The gaseous radioactivity consists principally of argon-41, which is contained in shield cooling air and in carbon dioxide coolant. Particulate airborne wastes discharged may include fission products but at CEGB stations consist mainly of activation products (such as ^{60}Co and ^{59}Fe).

Generally filtration to remove particulate radioactivity is the only treatment given airborne discharges before their release to the atmosphere, which is usually through a stack. Leakage from the pressure circuit is swept usually through filters to the atmosphere by ventilation or shield cooling air. An exception to the general method of treatment of airborne waste is that used to treat carbon dioxide discharges from Series G reactors at Marcoule, in France, where the coolant is liquified and retained for further use.

Aqueous liquid waste produced in the reactor itself is limited to induced activity in the water used to cool the concrete in concrete pressure vessel reactors and, in UK reactors, tritiated water formed in water vapour present in the pressure circuit and tritium produced mainly by neutron irradiation of lithium impurities in the graphite of the reactor core. This tritiated water is collected in the circuit driers used to limit moisture levels in the pressure circuit. Wastes are also produced in changing rooms, active laundry, decontamination facilities and so on, though these would not normally contribute large quantities of radioactivity to wastes from the station as a whole. By far the largest contribution to the activity of liquid effluent from all but one of the stations operated by the CEGB is made by the storage of spent fuel in cooling ponds, where it is kept for a time to allow its radioactivity to decay before it is sent for reprocessing. The water from these ponds is circulated through an ion exchange treatment plant, the regenerant liquors from which, after neutralization, are handled with other liquid effluents.

Filtration is usually all that is required for treatment of liquid effluents. After filtration and monitoring for radioactive content the effluents are discharged to a large body of water. Discharges from CEGB reactors are made, after dilution with the very large volume of condenser cooling water (some 90 000 m^3 / hour per station), to the sea or to an estuary; in one case, at Trawsfynydd, the discharge is to a freshwater lake. The liquid radioactive discharges from the French reactor establishments at Marcoule, Chinon and St.Laurent des Eaux are made to rivers with large rates of flow. At Trawsfynydd the limitations on discharges are more stringent than at other UK stations, and this installation is provided accordingly with non-regenerable ion exchange beds in the effluent treatment plant. At most CEGB power stations the radionuclides making the greatest contribution to the radioactivity of liquid effluents are ^{137}Cs and ^{134}Cs, which arise in the cooling ponds. The levels of these nuclides at a number of stations have become high enough to require the installation of ion exchange or preferential adsorption plants especially to remove them. During the past few years isotopic analyses of liquid effluent from the power stations has been carried out both to establish the composition and to indicate any changes which could affect the critical route of population exposure to radiation. The sludges, spent ion exchange materials, filter backwashings and so on, which arise in the treatment of liquid wastes, are themselves treated as solid wastes.

In both the UK and France central facilities for the accumulation of radioactive solid wastes are available, but in the case of the CEGB stations solid wastes ar usually accumulated at the station at which they arise. The Electricité de France stations use this latter arrangement for large volumes or for high activity wastes. The fuel element fins are removed from the spent fuel at CEGB stations before it is despatched for reprocessing, these magnesium alloy fins constituting an important part of the solid radioactive wastes which are created. Non-combustible solid wastes include filter backwashings and ion exchange materials from the pond water and liquid effluent treatment plants, together with miscellaneous scrap items of plant and equipment which have become contaminated or activated in use. Substantial quantities of combustible solid radioactive wastes are produced, including active waste from changing rooms and sisal Kraft paper and plastic sheeting used to minimise spread of contamination during certain operations in the power station.

Where possible, it is obviously preferable to reduce the volumes of wastes before accumulating them. The method now used widely in the UK for combustible waste is incineration. Incinerators are designed carefully to prevent significant discharge of radioactive materials to the environment. The ash from incinerators may be accumulated in the same way as other solid wastes or, when it is of very low radioactivity, it may be dumped at suitable public rubbish tips. More highly radioactive combustible wastes than those suitable for incineration are accumulated in vaults. In France compression is used in addition to incineration to reduce the volume of solid wastes before containment and accumulation.

Non-combustible wastes are also accumulated in vaults having adequate shielding for the type of material they are to contain. It is ensured that the vaults do not allow leakage of radioactivity to the ground, especially when their intended contents are wet – for example, sludges.

Operating Experience with Gas-Cooled Reactors

The gaseous discharges are mainly of argon-41, of which some 10 mCi/sec may be expected from a typical UK steel pressure vessel power reactor. The half-life of this nuclide is fairly short – 110 minutes – and it is discharged to the atmosphere in such a way that it is difficult to detect in the environment. At Chinon the average gaseous discharge (again, mainly ^{41}Ar) in 1970 was about 250 μCi/sec.

Table VI.
CEGB Nuclear Power Stations Discharges of Radioactivity in Liquid Effluent in 1970

Station	Radioactivity Discharged in 1970: Tritium (Ci)	Radioactivity Discharged in 1970: Radioactivity other than Tritium (Ci)
Berkeley	60.1	23.2
Bradwell	95.3	129.2 (0.085)
Hinkley Point 'A'	18.6	127.7
Trawsfynydd	67.7	13.5
Dungeness 'A'	18.6	83.7
Sizewell	20.9	23.4
Oldbury	17.3	7.74
Wylfa	0.551	6.32

Notes

1. Figures shown in brackets for Bradwell refer to zinc-65
2. Wylfa discharges of radioactivity other than tritium were due almost entirely to bromine-82 discharged during tracer tests on cooling water pumps.

Deliberate discharges containing particulate radioactivity — mainly of activation products — from CEGB reactors amount to only a few millicuries per month per reactor, and have had no significant effect on the environment.

The radioactive content of liquid wastes discharged to the aquatic environment is limited to levels laid down as appropriate for the particular power station by the competent authorities. At Chinon, where discharge is to the River Loire, the radioactivity released in 1970 was only about 2.25 curies. In the UK discharges are mainly to an estuary or to the sea; Table VI summarizes discharges from CEGB nuclear power stations in 1970. In most cases little or no activity has been measurable in the aquatic environment as a result of these discharges.

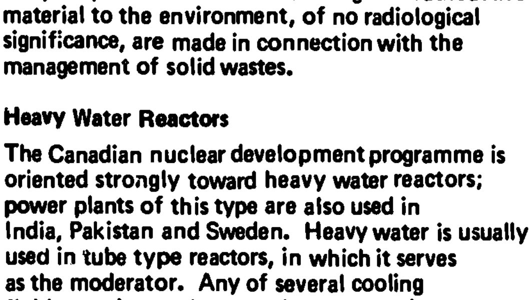
Only very small deliberate discharges of radioactive material to the environment, of no radiological significance, are made in connection with the management of solid wastes.

Heavy Water Reactors

The Canadian nuclear development programme is oriented strongly toward heavy water reactors; power plants of this type are also used in India, Pakistan and Sweden. Heavy water is usually used in tube type reactors, in which it serves as the moderator. Any of several cooling fluids may be used — organic compounds, gas, water or heavy water — since the heavy water moderator is separated physically from the coolant. The net fuel consumption of heavy water reactors is quite low, and they can operate on natural uranium.

The heavy water moderator is contained in a tank surrounding the fuel containment tubes (Fig.15). There is room in the fuel tubes for the coolant to flow past the fuel elements, thus removing the heat that is generated in the fuel. The coolant then gives up its heat in a steam generator, as in other types of reactor power station.

Figure 15: Schematic diagram of a typical heavy-water reactor



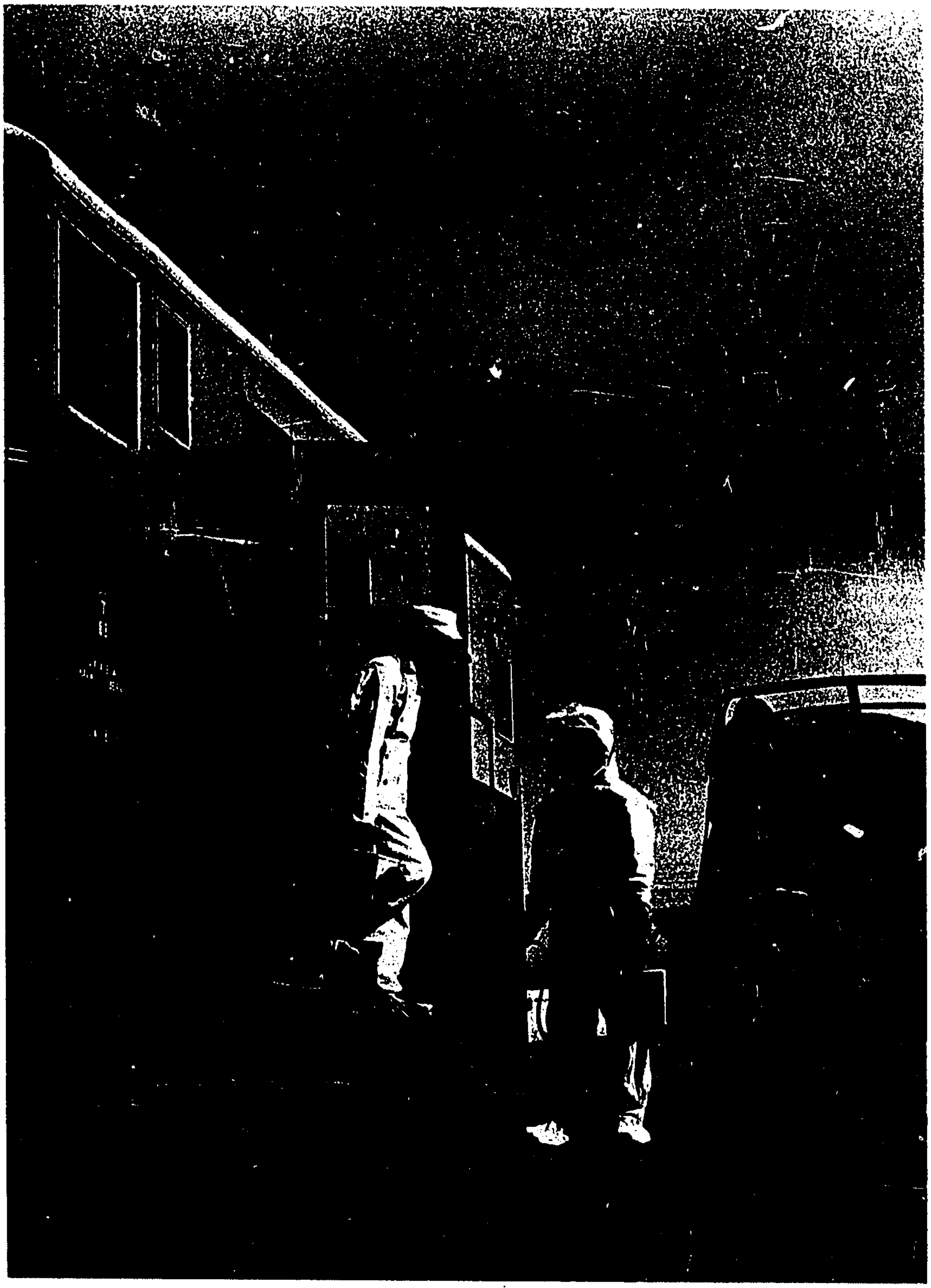
Canadian experience with heavy water power reactors has been limited so far to the Douglas Point Generating Station (220 MW(e)), which has been operating since November 1966, and the Nuclear Power Demonstration reactor (NPD — 25 MW(e)), which has been converted from pressurized heavy water to a boiling heavy water coolant. The 250 MW(e) reactor at Gentilly in the Province of Quebec is cooled with boiling light water, and in November 1971 had operated for one year only. The first unit at the Pickering site went critical in February 1971.

Heavy Water Reactor Waste Management

With the exception of the rather larger inventory of tritiated water (about 1 Ci/kilogram in the primary heat transport system at equilibrium) heavy water reactors are otherwise similar to pressurized water reactors with respect to their potential release of radioactive materials to the environment. Radioactivity in wastes results either from the escape of fission products from failed fuel elements or from the neutron activation of impurities or corrosion products circulating in the coolant. Soluble radionuclides such as those of caesium remain in solution in the coolant and escape from the reactor when the water leaks or during fuel changing. Less soluble radionuclides such as those of cobalt tend to be deposited on the surfaces of piping and normally do not escape with the coolant. Instead, they are released when equipment is decontaminated either in situ or prior to out-of-service maintenance. Gaseous radionuclides such as those of the noble gases and iodines become airborne if they are present in the coolant, if and when it leaks.

The rates at which fission products escape from the fuel depend directly on the rate of fuel failure. However, since it is possible to change fuel without shutdown in the CANDU-type reactor being discussed, with adequate provision for detecting and locating failed fuel it is possible to remove defective elements and thus to keep to a minimum the amounts of fission products that escape to the coolant.

The amounts of activation products formed depend on the presence of parent atoms in contact with the coolant. ^{60}Co arises in part from the presence of cobalt-bearing alloys, especially those of high cobalt content such as Stellite in positions where they are exposed to heavy wear, and also from corrosion of components which, though low in cobalt, have a large amount of surface area in contact with the coolant. ^{65}Zn arises from corrosion



of valve-packing, which may contain as much as 50% zinc.

The amounts and composition of radioactive materials available for release can thus vary considerably from one reactor to another of the same type. Similarly, the fraction of the radioactive materials present in a reactor which may escape to the environment also varies depending on a number of factors associated with the design details. Of particular significance to the heavy water reactor is the economic incentive to reduce heavy water leaks to a minimum. For example, gaseous ventilation streams from areas containing high-pressure systems are closed cycles fitted with molecular-sieve driers to recover heavy water vapour. The driers also remove tritiated water vapour so that the amounts of this radionuclide available for release to the atmosphere are very much less than they might otherwise be without special provision for its removal. The driers also remove iodine and caesium nuclides from the air streams, though whether the iodine is retained during the drying cycle is not yet known. Also all leaks of liquid heavy water from low-pressure systems are collected as far as possible in tanks for heavy water recovery. At the same time dissolved radionuclides are also collected, thus providing for finer control over the subsequent fate of these wastes.

The need for closed-cycle ventilation to recover heavy water also provides, incidentally, for delay in the release of noble gas radionuclides. This delay means that radioactive decay reduces significantly the amounts of the short-lived nuclides which are released to the atmosphere.

The NPD and Douglas Point reactors are designed to have air cooling of the space between the callandria tubes and pressure tubes. Thus, in these reactors ^{41}Ar is produced in substantial amounts, although the fraction which escapes is generally relatively small because of the closed-circuit ventilation. In the Pickering reactors these spaces will be cooled using dry nitrogen and no ^{41}Ar will be produced.

Delays in the liquid systems similarly allow time for substantial fractions of the short-lived radionuclides to decay before being released to the environment. In general, radionuclides having half-lives of less than 10 days are reduced by this means to insignificant levels before they are released.

Tables VII and VIII summarise the releases of radioactivity to the atmosphere and water respectively from the three Canadian power reactors. Although releases from the Gentilly reactor during the first 10 months of 1971 have been included in the tables it is too early to assess the long-term situation. Indeed, in all three reactors modifications have been made and continue to be made, affecting to a greater or lesser extent the amounts and composition of the radionuclides which will be available for release to the environment. It is not possible to extrapolate from the limited experience gained so far in operating the CANDU-type reactor with its many possible variants.

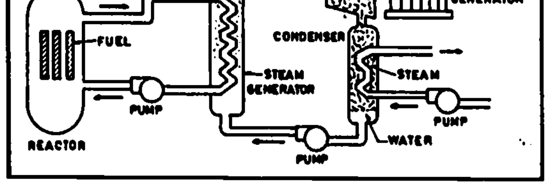
Fast Breeder Reactors

Breeder reactors are those which may be used to transform fertile materials such as ^{238}U into fissionable materials such as ^{239}Pu or Thorium into ^{233}U by neutron absorption, thus creating more fuel than they consume. Several designs of reactor have a potential for breeding. To date all known fast breeder reactor projects are based on reactors with sodium-cooled primary circuits, in which the sodium is blanketed by an inert cover gas (argon) at close to atmospheric pressure. Systems and components for the breeder differ from those of other reactor types. There is an intermediate heat-transfer loop between the reactor coolant system and the generator of steam to drive the turbine (Fig.16).

Production and management of waste in fast-reactor nuclear power stations

The waste problems presented by this type of reactor are associated with sodium and the technology of handling it, with plutonium and also with the characteristics of the neutron flux within the reactor, in terms of its energy, density and so on.

Figure 16: Schematic diagram of a typical liquid-metal cooled fast breeder reactor



Decontamination facilities for industry: A mobile control unit carrying a full range of equipment, which can be taken quickly to the scene of a radiation accident. Photo: UKAEA

Table VII.
Average Releases of Radionuclides to the Atmosphere from Canadian Power Reactors

	Average Daily Releases (Ci)				
	1967	1968	1969	1970	1971
Douglas Point					
Noble Gases	1	110	280	440	NA
Tritium (oxide)	0.6	7	26	30	NA
^{133}I	ND	2×10^{-4}	5×10^{-4}	6×10^{-4}	NA
NPD					
Noble Gases		..	45	..	NA
Tritium (oxide)	25	27	28	21	NA
^{131}I	ND	ND	ND	ND	NA
Gentilly					
Noble Gases					Trace*
Tritium (oxide)					34*†
^{131}I					ND*

ND = Not detectable
NA = Not available
* = First 10 months only
† = Includes accidental releases. Excluding accidental spills the average daily release is less than 2 Ci day^{-1}

Table VIII.
Liquid-Waste Discharges from Canadian Power Reactors

	Average Daily Releases (Ci)				
	1967	1968	1969	1970	1971
Douglas Point					
Mixed Radioelements†		15×10^{-3}	33×10^{-3}	58×10^{-3}	NA
Tritium (oxide)		1.2	2.7	2.6	NA
NPD					
Mixed Radioelements	2.1×10^{-4}	4×10^{-5}	5×10^{-5}	6×10^{-5}	NA
Tritium (oxide)	10.1	15.9	14.8	9.6	NA
Gentilly					
Mixed Radioelements					1.2×10^{-3} *
Tritium (oxide)					2.9*

NA = Not available
* = First 10 months only
† = The average composition of the mixture during the first six months of 1971 is thought to be typical and is as follows: ^{137}Cs, 58%; ^{134}Cs 20%; ^{60}Co 17%; ^{131}I 4.3%; ^{65}Zn 0.2%, ^{54}Mn 0.3%; ^{58}Co 0.2%; ^{90}Sr < 0.05%; ^{89}Sr < 0.001%.

Activation of the primary sodium and its propensity to trap iodides (NaI), fission products and activation products constitute the main cause of contamination. Moreover, most of the noble gases released by the fuel as a result of cladding failures turn up in the argon cover gas, and it has been found necessary to design primary circuits which ensure very effective containment. Two basic designs can be envisaged at the present time; the primary containment of each is extremely leaktight.

Of these two designs (circuits with external heat-exchangers, and circuits of the integrated type), we shall discuss only the latter in order to avoid dealing with two different examples. It is probable in any case that routine waste management problems would not be solved very differently in the two cases. The integrated circuit type has been chosen in Soviet (BN 600), British (PFR) and French (Phénix) projects.

In this design the main reactor vessel, which also encloses part of the handling machinery and equipment, is itself enclosed in a primary containment vessel of such a size that rupture of the main reactor vessel would not entail loss of coolant from the core.

Fission products liberated from the fuel as a result of cladding defects, corrosion products entrained in the sodium and activated corrosion products from elements subjected to the neutron flux are normally contained in the leak-tight primary containment vessel. However, the handling of core components and items from the primary circuits necessitates an infringement of this integrity. The primary sodium and argon circuits for present projects are enclosed only partly in the primary containment, but it is foreseeable that for large industrial-size reactors they will be completely within the containment.

Waste management control

. . . Gaseous wastes

The essential part of the primary sodium circuit is contained in the main reactor vessel. It has been accepted on the basis of experiment that 0.1% of the solid fission products and iodine compounds (NaI) released into the sodium as a result of cladding defects would reach the argon; 90% of these elements, released from the sodium in the form of aerosols, would be deposited subsequently on cold parts of the primary circuits (the part of the reactor vessel outside the sodium, purification loops of the primary circuits, and so on).

The argon circuit, whose complex rôle is to provide a neutral atmosphere in all the parts containing sodium, to regulate the pressure of the argon blanket, to allow recycling, scrubbing, scavenging and discharge of part of the argon, is equipped with devices allowing the fluid to be cleared of entrained sodium aerosols and of the solid daughter products of the noble gases. The sources will therefore be localized principally at these devices. As noble gases are not retained by the sodium to any appreciable extent, it is found useful generally to postpone the discharge and scrubbing by passing the recycle gas through baffled delay tanks.

The gaseous releases constitute normally the main possible source of contamination of the environment, and are subjected to special monitoring; their treatment is such that these releases can be made very small when necessary.

After decay in the tanks provided for the purpose only long-lived gaseous isotopes remain; these are then trapped on activated charcoal at low temperature before discharge. Any radioactive particles that might still remain in the gas are filtered by highly-efficient absolute filters in the ventilation system of the reactor lding.

After desorption of the charcoal from the purification plant the gases are stored until the ^{123}Xe has decayed; ^{85}Kr is then the only important remaining isotope. One then has the alternatives either of disposing of it by spreading out the release over a period of time and awaiting favourable conditions, or of storing the desorbate in bottles (which requires long-term storage since ^{85}Kr has a half-life of about 10 years'.

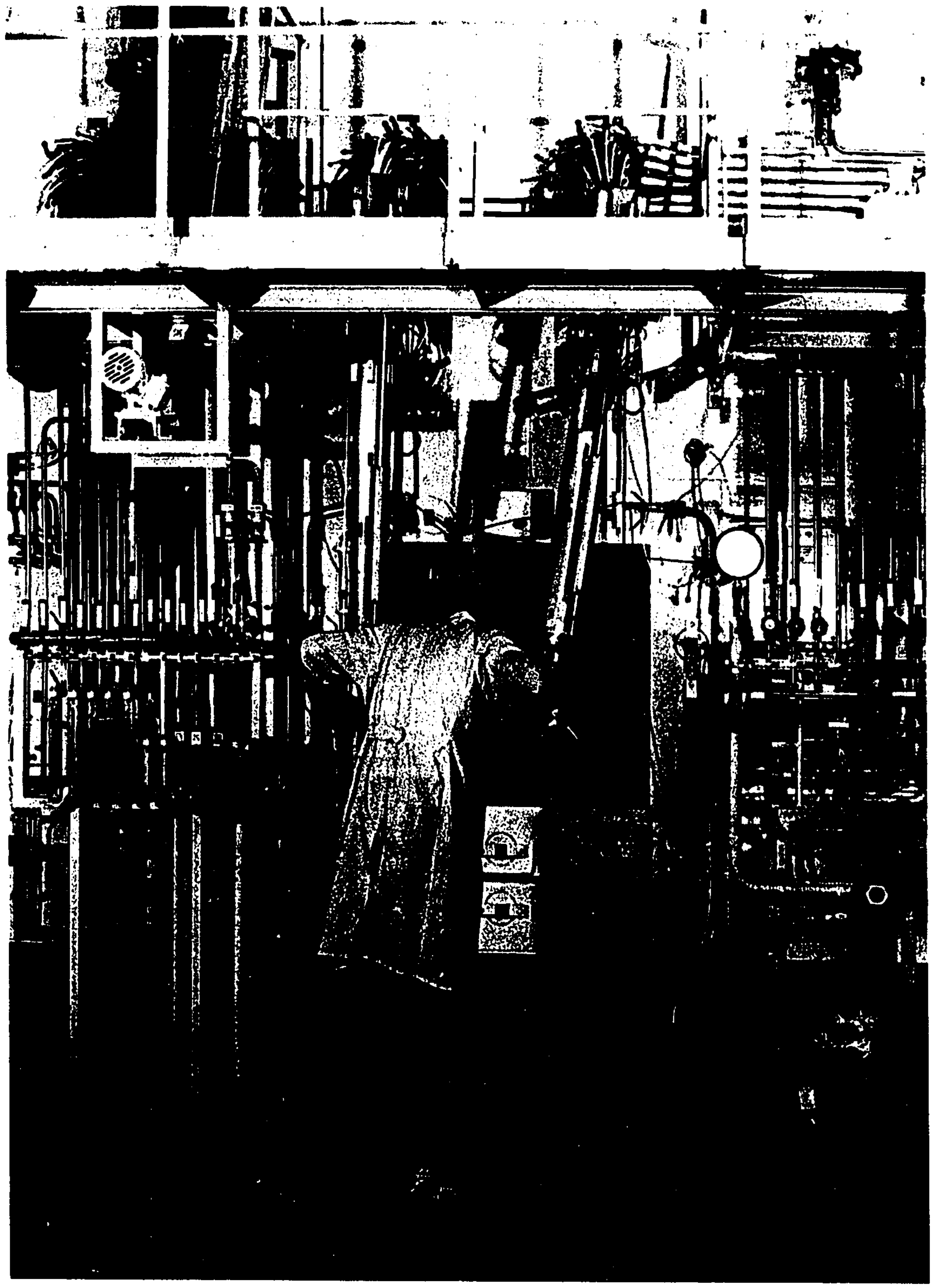
Monitoring consists in measuring activity at several points in the argon circuit:

the outlet of the devices used for filtering sodium aerosols;
the outlet of the decay tanks;
and the outlet of the scrubbing cell.

The general detector for monitoring the activity of waste in the ventilation gives a final indication of the character of the gaseous waste. Finally, the waste is diluted substantially in the stack.

. . . Liquid wastes

Liquid wastes arise from decontamination of the inside of the primary circuit devices; from



decontamination of small equipment;
from washrooms, showers and change facilities;
from hot cells and from workshops; as
residue from combustion of sodium
(if a fire were to occur in the primary sodium coolant); and, finally, the sodium from the primary coolant loop if it must be removed. In addition to the constituents normally found in the liquid wastes of other types of reactors, the liquid wastes of fast breeder reactors generally contain sodium hydroxide (NaOH) and traces of plutonium.

Monitoring of liquid wastes is carried out at each stage by sampling:

intermediate checks before collection;
checks before transport to the effluent treatment plant;
checks before treatment (radiochemical analyses);
checks before disposal.

It is possible to dilute the effluents once they have been collected for storage. After collection and storage the effluents pass through a sealed drainage system or are transported in tank cars to an effluent treatment plant, which may serve several power stations. In the event of an accident it is possible to reserve the existing capacity for effluents of high and medium activity and to use auxiliary capacity for low-activity effluents.

The treatment of liquid waste depends on the activity level and the chemical composition of the waste. Only the large quantities of effluents containing soda may cause special problems.

Low-activity effluents are subjected to a simple check and neutralized, if necessary, before disposal outside the power station.

Medium- and high-activity effluents are filtered to remove suspended material and the filtrate is treated by ion exchange, evaporation or flocculation, as required. After monitoring the low-activity liquids are discharged into the river and the concentrates are treated as solid wastes.

The total activity and the activity level of the waste discharged are kept within limits based on the minimum dilution volume (taking into account any other releases of radioactive materials upstream and downstream) in order to ensure that the maximum permissible concentration (MPC) for drinking water [less than 10^{-7} Ci/m^3 for an unidentified mixture of radionuclides if neither ^{226}Ra nor ^{228}Ra is present] is not exceeded.

The service area of dissolving cells at the Karlsruhe research centre. Photo: Ges. für Kernforschung m.b.H., Karlsruhe

Surveillance of the biological environment is carried out by means of periodic sampling down-stream, and analyses of flora and fauna.

. . . Solid Wastes

High activity solid wastes consist of the cladding of fuel assemblies (when they are dismantled on site); non-reusable components such as pumps, heat exchangers, rods and rod drives; purification devices and concentrates from the effluent treatment plant. After containment of contamination and protection from irradiation, which are achieved by the usual methods, these materials are stored either on site or, better, at a special storage site.

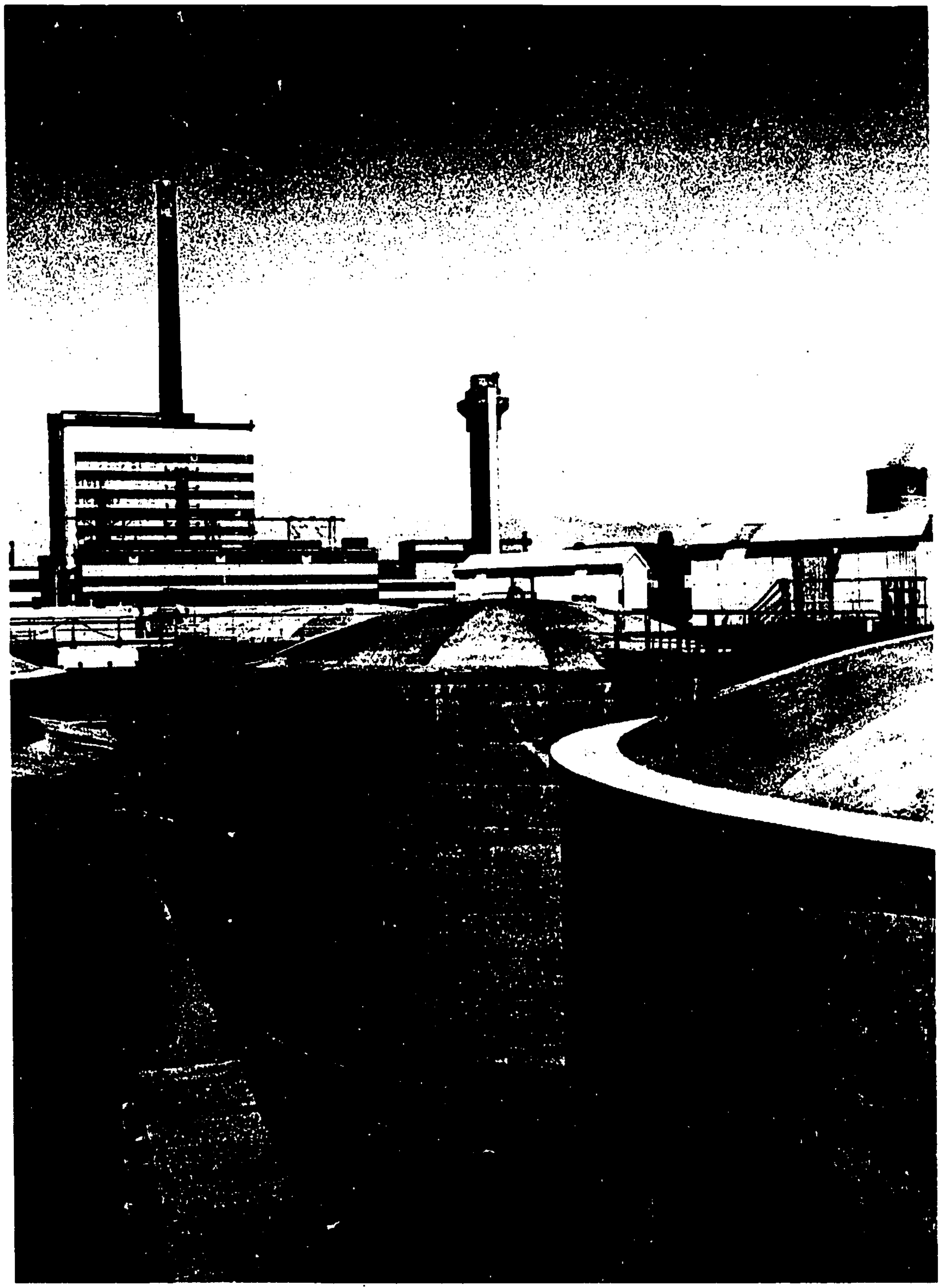
Low-activity solid wastes vary in volume and type, but are usually compacted, chopped and packed in drums after being enclosed in vinyl. They can be kept at a special storage site. Burnable low-activity waste is incinerated whenever possible.

The various concentrates, filter media, resins and other solid wastes from the effluent treatment plant are incorporated in bitumen and stored at a special storage site.

Conventional monitoring methods are used, including external radiation checks by portable or fixed monitors and contamination checks using monitors or smear tests.

Accident Considerations

All complex systems are subject to a wide variety of unplanned occurrences which may interfere with their normal operation or, in extreme cases, may endanger the health and safety of the public. Most accidents that can be envisaged for a nuclear power plant would have insignificant radiological consequences, but in practice the response of the plant to a variety of assumed accidents is examined in order to make certain that all potential avenues of release of fission products are understood. The probability of occurrence of the most serious accidents is exceedingly small - but for public safety any hazard outside the plant must be prevented. This requirement is accomplished by two basic approaches: first, the attainment of thoroughness and assured high quality at every stage from conceptual design to plans for unexpected emergencies; and secondly a parallel effort to prevent accidents which may occur from endangering the public, using several lines of defence. Obviously, the first approach pervades the second.



Accident prevention

The most logical way to assure safety in the ideal case would be not to allow accidents to happen. In practice, accidents may be minimized by making certain that the quality of each component and product used in a system is the highest attainable. The discussion which follows describes the approach adopted in the United States, but the philosophy which lies behind it is common to other countries.

"Quality assurance" ensures proper design, fabrication, construction and operation of - and hence confidence in - systems which protect the health and safety of the public. A great deal of stress is laid upon disciplined engineering and quality assurance; guidelines for quality assurance programmes have been added to the laws governing the construction, licensing and operation of nuclear installations. These guidelines outline the philosophy to be adopted in design, fabrication, procedures, procurement, handling, storage, identification, inspection, testing, records and audits, and apply at every step in design and construction.

. . . Attention to design

Familiarity with the system and an appreciation of the incidents, large and small, that can occur within that system are necessary if its design is to reflect safety consciousness adequately. Consideration is given to such things as

- the placement of relief valves so that their discharges do not impinge directly upon other pieces of equipment that might be damaged;
- the design of electrical equipment to specifications which ensure that it will continue to operate in the environment which might accompany an accident — for example, conditions of high temperature, pressure or humidity;
- multiplication of instrumentation to make up for data that might be lost because of faulty maintenance or because of an accident;
- and piping and pressure vessel design, and plant layout, so as to avoid potentially hazardous situations — for example, the integrated pressure vessel/piping/steam generator system for the gas-cooled reactor precludes the "double-ended" pipe break accident.

In addition, emphasis is given to designs which allow straight-forward and uncomplicated performance of routine tasks, and minimize the possibility of less hazardous but sometimes more probable accidents. Accidents such as those involving failure within the radioactive waste management system, fuel handling equipment malfunctions or human error - even though these are not likely to affect the public - have caused more difficulty in real situations than the large, hypothetical accidents that are planned for but have not occurred and are not likely to occur in future.

Effluent storage tanks at the Windscale reprocessing plant. Photo: UKAEA

. . . Attention to fabrication and construction

Care in workmanship and thorough checking and inspection do much to guarantee the safety and reliability of each component and ultimately of the entire plant. Some of the most costly and time-consuming problems encountered during plant construction and operation have been caused by failure to adhere to specifications dealing with identification, cleaning, welding and types of materials to be used. These may be considered details, but they are important details. With these and other facts in mind many positive actions have been taken to establish and to enforce quality assurance in nuclear plants to provide for their safe and reliable operation.

. . . Attention to procedures

It is necessary in a complex nuclear plant to establish, maintain and follow detailed operating, maintenance, periodic in-service testing and inspection, and safety procedures. This programme should be conducted normally by the plant operators in a manner approved by the relevant regulatory body. Variables which are significant to the overall safety of operation of the plant, governing the application of these procedures, are identified and monitored.

Safety limits on plant operating variables are established to protect barriers preventing the release of fission products. If a safety limit is exceeded then the plant is shut down, before the barrier can be breached. Similarly there are limiting system settings: settings so chosen that automatic action is taken to alleviate a potentially serious situation before the safety limits are reached. In this case the plant need not be shut down, but its operating condition is changed in order to maintain an adequate safety margin. Conditions relating to the functional capability of equipment required for safe operation are specified, and if performance of this equipment fails to meet these limiting conditions then remedial action must be taken, or the plant shut down. Other requirements of the technical specifications for the operation of nuclear installations are surveillance programmes, the various administrative controls necessary to the smooth running of a plant, and allowable limits for the release of effluents from it.

Accident mitigration

As noted previously, heavy emphasis is placed on the prevention of accidents to assure safety; but systems and devices are also provided to minimize further any possible hazard to the public by mitigating the effect of an accident should one occur. This philosophy has been called "defence in depth"; it includes attention to the protection of the public at every step from design to operation. Specifically, it includes the provision of barriers to the release of fission products, which are inherent in system design, and special "engineered safety features".

... Barriers

The fission process generates radioactive materials in the fuel, some of which are gaseous or volatile. Their escape is prevented by the fuel element cladding (of stainless steel or zircaloy) or, in the case of the high-temperature gas-cooled reactor, by layers of pyrolytic carbon and silicon carbide on the fuel particle. The cladding of some of the fuel is subject to minor faults in normal operation, but major failures are unlikely. However, in light water reactors any fission products that do escape from the fuel cladding are then contained by a very carefully designed and constructed primary piping system which, in turn, has a very low probability of failure. This is itself enclosed within the containment building, the final barrier, which is designed and constructed carefully to withstand the maximum pressure and temperature that could result from the "design basis" accident.

... Engineered safety features

A device or system which prevents an accident or limits its consequences is called commonly an Engineered Safety Feature (ESF). In the design of ESFs the principles of redundancy, diversity, freedom from "common mode" fault and single failure susceptibility are applied. The largest and most expensive ESF is the containment building which surrounds the nuclear portion of the plant. One of the simplest is the orifice in the main steam line of a boiling water reactor which restricts flow and lengthens blowdown time in the unlikely event of a pipe break. Between these two extremes there are core cooling systems, emergency power systems, containment atmosphere cleanup and cooling systems, double contained penetrations, control velocity limiters and many others.

Typical accidents

In the design of nuclear power plants it is common practice to consider hypothetical accidents which might have severe consequences, then to design the plant and its safety features in such a way that a hypothetical accident can be accommodated without risk to the health and safety of the public. As experience has increased, it has been noted that such "limiting" accidents have not occurred, but failures of a less severe nature have. Consequently, designers give just as much attention to the less severe accident. We will consider here first the failures that have an appreciable probability of occurrence but are not likely to give rise to a significant radiological hazard; then identify the precautions taken for each reactor type. It should be pointed out that no power reactor can tolerate an accident that involves complete and permanent loss of cooling capability; as a result, this accident is guarded against so well that its probability of occurrence approaches zero.

Some events analysed involve abnormal operating transients which are not considered to be accidents since no fuel damage results. Such an event sets in motion a chain of corrective actions which result either in a reduction power or the orderly shutdown of the reactor.

Occurrences that are analysed generally are loss-of-load (generator trip); loss of condenser vacuum; turbine trip; turbine bypass valve malfunction; and loss of power. Various sensing devices provide information to the control room operator and to instrumentation necessary to ensure that a transient is accommodated in an orderly fashion.

Other, more serious events that are analysed are considered to be accidents. These events also result in the shutdown of the plant, but they may also result in some release of radioactivity from the fuel or the primary system. The types of events analysed are accidents resulting from: introduction of reactivity to the core (by sudden withdrawal of control rods, causing the power of the reactor to increase); refuelling operations; or loss of cooling capability. In any of these events the ESFs may be called upon to perform their designed functions.

Figure 17: Safety features of a typical BWR

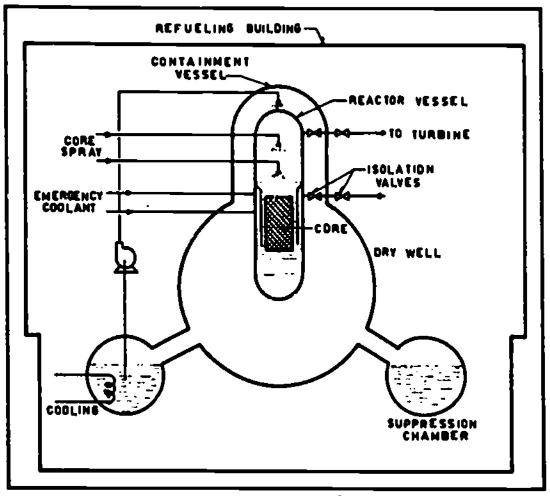
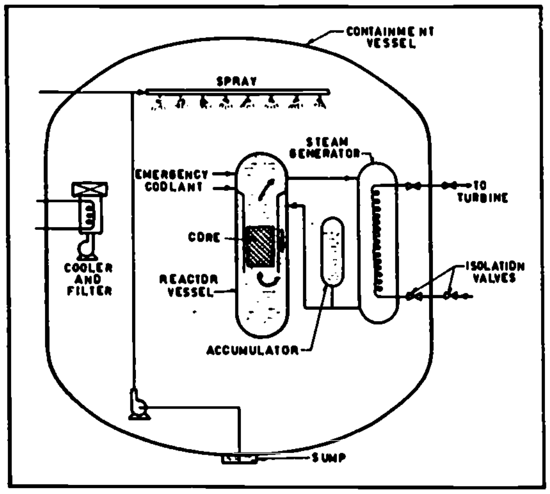


Figure 18: Safety features of a typical PWR



Such an accident is known as a "design basis accident", and is used to set the criteria for performance of many ESFs and in consideration of siting and safety generally. In addition, the designer assumes that some of the ESFs may fail in part: but the containment and emergency cooling system are assumed to work. These assumptions are thought to be quite conservative, and this type of analysis does allow an assessment of the safety of the plant to be made in the context of the possible effect of an accident on the public. Even under the adverse conditions assumed the radiation doses estimated to be likely to be received by the surrounding population are small.

... Light water reactors

The most serious hypothetical accident considered for light water reactors (both PWRs and BWRs) is that of loss of coolant: a failure in the primary system allowing coolant to flow unimpeded from both sides of the break is assumed. The Engineered Safety Features in this case provide for cooling water to be injected, poured or sprayed into the reactor vessel in order to minimize damage to the core (Figs 17 & 18). If these systems operate satisfactorily the accident is limited to pressurization of the primary containment by the release of high temperature water (a significant portion of which will flash to steam), the failure of a portion of the fuel cladding, and the release of some volatile fission products. These fission products would be filtered or scrubbed by one of the containment cleanup systems and a significant fraction would be removed. In any event, gross release to the environment would be prevented by the primary containment vessel.

... Liquid metal fast breeder reactors

The coolant for the liquid metal fast breeder reactor (LMFBR), as noted earlier, is liquid sodium at high temperature but at relatively low pressure (Fig.19). Of several hypothetical accidents postulated the worst is thought to be loss of coolantflow accompanied by failure of the control system to initiate a reactor scram (sudden shutdown). The designer assumes simultaneous failure of all operating primary sodium pump motors, and thus loss of coolant flow. If this combination of failures were to occur the sodium would boil. Voids within the sodium resulting from this boiling would tend to increase the reactivity of the reactor - in other words, its condition would become supercritical, and its power would increase rapidly. This would lead to melting and partial vapourization of the fuel, and eventually to disassembly of the core. [The energy released in such an event would be limited by physical factors which are calculable.] A quantity of sodium coolant would be forced upward against the reactor plug, leading to a loss of pressure and the release of a fuel/sodium aerosol to the galleries and compartments around the reactor vessel. Some of this released material could then leak into the space bounded by the containment shell, where most of it would be removed by the air cleanup system. The LMFBR is designed to ensure integrity of the primary vessel, head and heat transport system; in addition, a containment shell is provided to ensure that in the event of an accident such as that described the public would not be significantly affected.

Figure 19: Safety features of a typical LMFBR

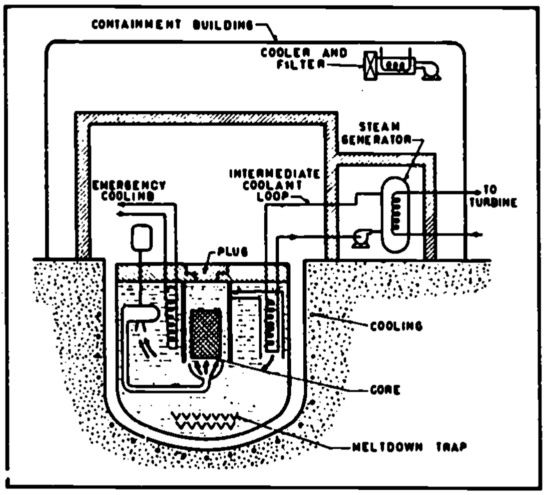
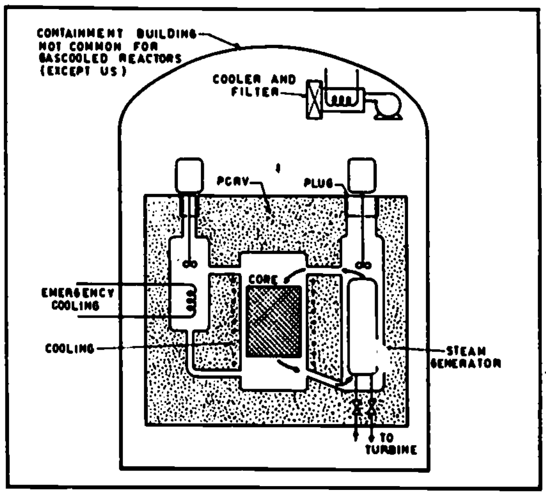


Figure 20: Safety features of a typical GCR



. . . High-temperature gas-cooled reactors

In a high-temperature gas-cooled reactor (HTGR) helium is circulated at a pressure of 50 atmospheres with an outlet temperature of 760°C through a core made up primarily of graphite, with pyrolytic carbon and silicon carbide coated uranium-thorium carbide fuel particles (Fig.20). Many of the very serious accidents normally considered in association with other reactor types are obviated by basing the design on an integrated core and steam generator system, using a prestressed concrete pressure vessel. One of the most serious accidents considered is a depressurization of the primary system together with failure of some steam generator tubes. In this highly improbable accident the rate of depressurization would be limited by the access plugs, which would act as loose-fitting "stoppers", Steam would be injected into the core through the break in the heat exchanger, giving rise to a graphite/steam reaction. This would release hydrogen, and would probably damage the core sufficiently to release some fission products from the fuel. The activity would then leak from the primary system and would be partially trapped in the containment cleanup system; gas leakage would be prevented ultimately by the containment shell.

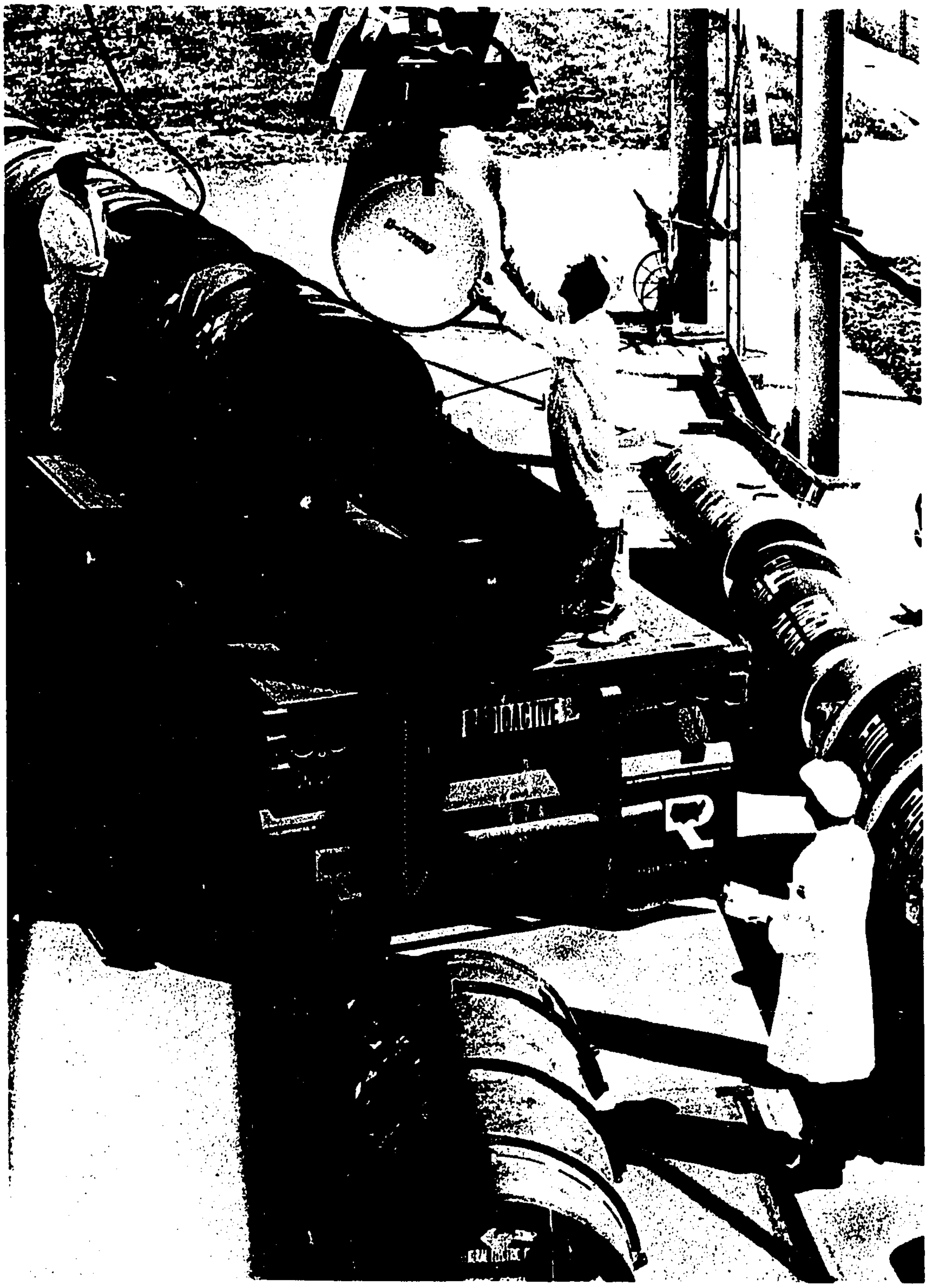
Emergency planning

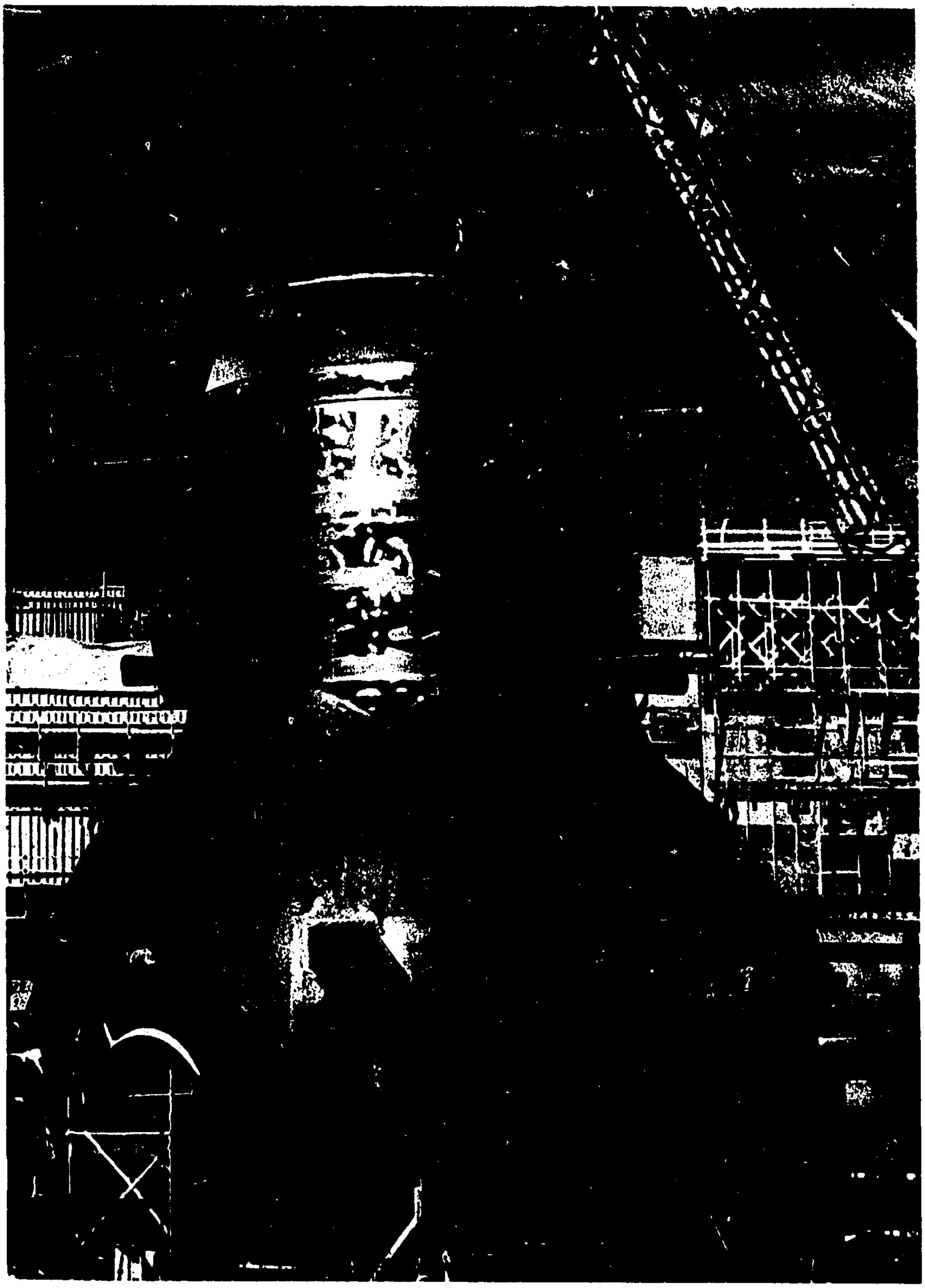
Most accidents are prevented by elaborate safety systems and designs, and if any does occur the Engineered Safety Features should be able to reduce the hazard to the public to an acceptable minimal level. But, as an auxiliary to Quality Assurance, "Defence in Depth" and ESFs, "Emergency Planning" is also required in respect of each installation. Plant operators are required to establish an organization made up of designated individuals, from both within and without the group responsible for plant operations, who must prepare for any emergency situation that could arise. Inter alia, they have the responsibility for ensuring safe shutdown and cooldown of the plant; the establishment of communication and working agreements with various community and governmental emergency and law enforcement agencies; the identification of the position and function of each member of the emergency organization together with any special qualifications they may have; the maintenance of a means of determining the magnitude of a release and the establishment of criteria for putting into operation various emergency plans and the establishment of procedures for notifying all involved parties and agencies; provisions for emergency treatment of injured at the site and at local medical facilities; provisions for training and practising the duties assigned to each member; and, finally, procedures for determining when it is appropriate to re-enter the installation affected.

Site characteristics

Choice of a reactor site often carries with it special design requirements, to take account of

Workmen at the Oak Ridge Gaseous Diffusion Plant load a cylinder of uranium hexafluoride, enriched in uranium-235, for shipment. Photo: USAEC





seismic loadings, foundation conditions, wind and weather conditions, floodings and tidal wave considerations, land use and access and various other physical factors. In regions of the United States where seismic activity is to be expected a nuclear installation may not be located nearer than a quarter of a mile to an active fault; and it must be designed to withstand the maximum ground acceleration which has been experienced at the distance of the site from the fault. In areas where strong tornadoes are prevalent the assumed design condition is a 300 mile per hour wind with an associated pressure drop of 3 pounds per square inch in 3 seconds. The effects of the maximum expected flood or tidal wave are taken into account similarly, to ensure that the plant will be safe during and after the event.

Special situations arising out of surrounding land use may require special attention. If the plant is to be built in the vicinity of the flight path of a nearby airport the containment and other structures are designed to withstand the impact of a colliding aircraft. If agricultural conditions present an important pathway for the transfer of radionuclides to man the routine release rate(s) of the important fission product(s) are limited accordingly. If the plant is built near a population centre then many factors must be taken into account, and additional safety features provided. In all cases, any characteristic of the site that may have a bearing on the overall safety of the plant is considered, and appropriate protective measures are taken if needed.

Operating experience in the United States

It is now more than a quarter of a century since the first chain reaction was achieved. The intervening years have witnessed the installation and operation, in the United States alone, of some 25 central station nuclear electricity generating plants. During this entire period no single member of the public has been injured by a power reactor accident in the US - nor in any other country. Failures in the operation of these reactors have been experienced, but these failures were of a minor nature and the Engineered Safety Features of the plants concerned were capable of dealing with them. When failures occurred the plants were shut down safely, in accordance with their design.

The containment shell for one of the three reactor units at the Browns Ferry nuclear power plant, during construction. Photo: Tennessee Valley Authority

Abnormal occurrences and/or unusual events experienced must be reported to the regulatory agency. Such reports are reviewed to make sure that corrective actions taken are adequate; and, in addition, they are made available to other facilities and reactor designers throughout the country so that they may be aware of what has taken place. These "experience reports" are also available to the public.

Similar experience in the design and operation of nuclear power reactors has been obtained in other countries. It is important that such experience be gained, and that it be applied in the further development of additional Engineered Safety Features. In this way the reliability of reactors for safe operation can be improved even further.

Fuel Reprocessing

Fission products build up in fuel elements within the reactor, eventually absorbing neutrons to such an extent that the fission process is interfered with. The fuel elements are therefore removed from the reactor well before all the usable fuel has been burned, and are sent to reprocessing plants. The main objective of reprocessing is the safe and efficient recovery of plutonium (which is produced in the reactor) and unburned uranium in sufficient purity for re-use in the fuel cycle.

Although much research and development has been carried out on differing technical approaches to this objective, all the processes used in the world's major reprocessing facilities are based upon the dissolving of the fuel in aqueous acid, followed by a series of solvent extraction and sometimes ion exchange operations which first remove fission products, secondly separate the plutonium and uranium, and thirdly purify these two products. The discussion which follows therefore centres on this widely-accepted approach, which is unlikely to be superseded to any great extent for at least a decade.

Origins and types of effluents and wastes

In order to discuss the control of radioactive effluents and wastes arising during reprocessing it will be helpful to summarize the main types of operation, so that the origins of the various wastes are made apparent.

... Disassembly operations - It is sometimes necessary to remove external parts of the irradiated fuel assembly by remote methods prior to starting reprocessing operations proper. This gives rise to an accumulation of metallic waste which, as a result of neutron activation in the reactor, is usually radioactive.

... Decladding - Some fuels, especially uranium metal fuels, are treated to remove their cladding either by chemical dissolution or by mechanical processes. In the former case a liquid effluent results, and in the latter, solid waste in the form of a swarf. In each case the cladding activity, caused mainly by diffusion of fission products from the fuel into the cladding and by neutron activation, must be reckoned with in the waste.

... Fuel shearing - Other fuels, especially those made of uranium oxide, are fed to a shear and chopped into small sections which drop into a dissolver vessel. This operation may release small quantities of gaseous effluent, including radioactive noble gas fission products.

... Fuel dissolving - Metal fuels, after decladding, are dissolved usually in a boiling aqueous acid. This gives rise to a gaseous effluent containing radioactive fission products such as the noble gases radiokrypton and radioxenon, together with radioiodine.

Oxide fuels, after shearing into small sections, are also treated with boiling aqueous acid, giving rise to similar gaseous effluents. Sometimes the fuel and cladding are dissolved entirely, but more often only the irradiated uranium oxide is dissolved, leaving a residue of leached metallic hulls to be disposed of; these may be stainless steel activated during residence in the reactor, or zirconium or other alloy similarly activated.

... Chemical processing - The dissolver solution containing the uranium, plutonium and fission products is next processed in a series of solvent extraction and sometimes ion exchange treatments with intermediate chemical conditioning stages. At the outset the bulk of the fission products are separated to give an intensely radioactive waste, which must be stored in some form after further treatment and concentration. As processing for the recovery of the two major end-products - uranium and plutonium - continues a number of liquid effluents arise. These contain the remaining traces of fission products together with economically acceptable trace amounts of lost uranium and plutonium; after further treatment these effluents must be disposed of safely and economically. Some solid wastes, such as ion exchange resins, used filters and so on, of moderate activity level, also arise from these operations.

... Purification of products for recycling - The final stages of chemical purification of the plutonium and uranium products and their conversion to forms (usually oxides) in which they may be used again in the fuel cycle result in limited volumes of liquid and gaseous effluents containing minute traces of the products. Solid wastes deriving from the mode of handling the plutonium in these final purification and conversion phases are also created; these include materials such as plastic containment wastes and discarded rubber gloves, which imply a requirement for recovery and disposal.

Control of effluents and wastes

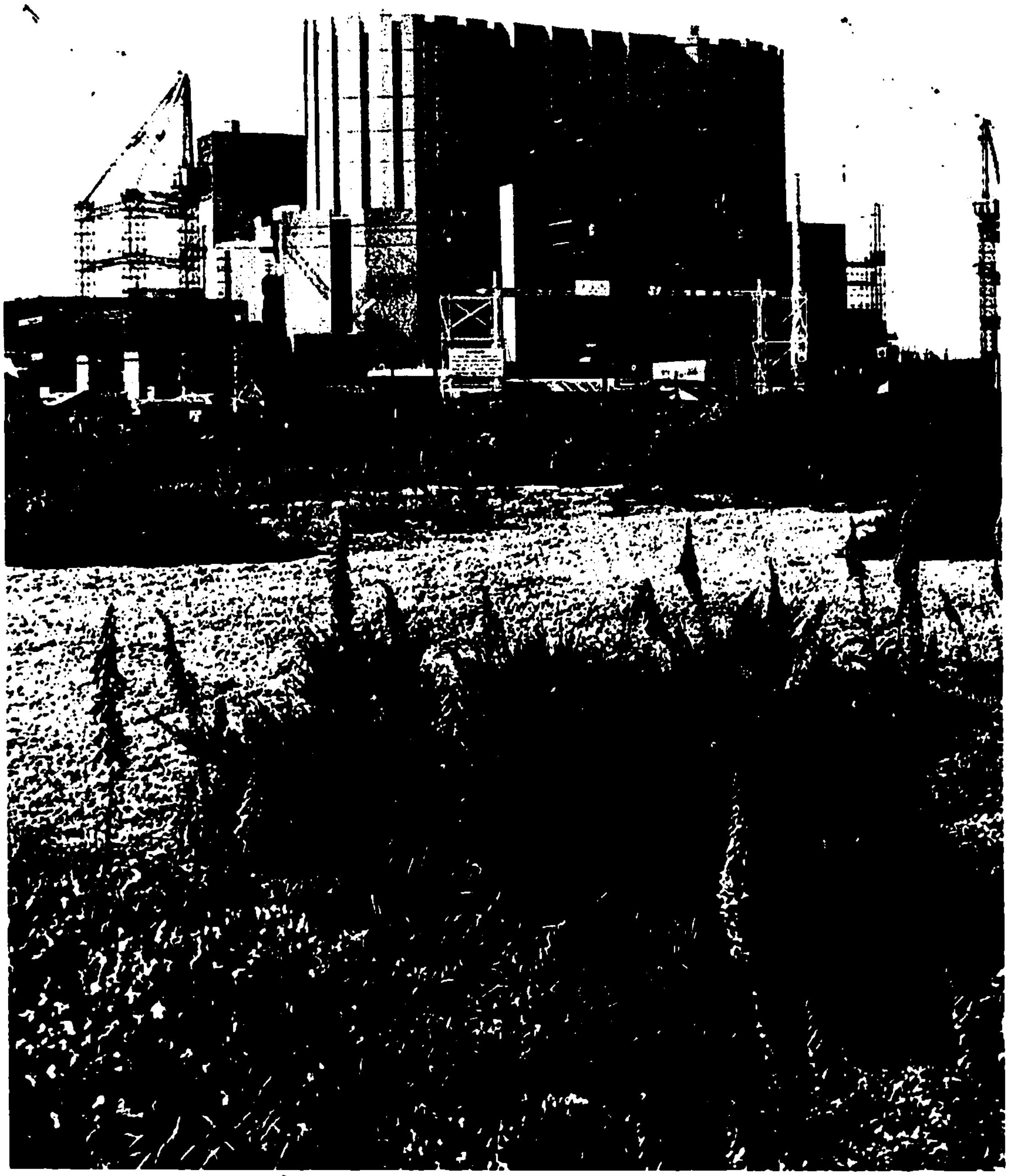
Having summarized briefly the origins and types of waste arising from fuel reprocessing, it is now possible to examine its management and control using for convenience as before the three collective headings - solids, liquids and gases.

... Solid wastes - The principal solid wastes are the metallic discards, cladding swarf and leached sections of fuel can. Usually these are too active for disposal by simple burial, although this procedure has been selected at some facilities where it has been established that suitably impervious geologic strata exist. More often these metallic wastes, which include commonly stainless steel, magnesium alloys and zirconium alloys, are stored in concrete silos on the site, designed and operated in such a way as not to preclude the possibility of ultimate removal and final disposal after a very long decay period.

Other solid wastes are monitored and segregated into convenient types - for example, combustible and non-combustible materials, and medium- and low-level activities. A variety of disposal techniques have been adopted for these wastes in different countries. For the lower levels of activity burial in large trenches on the reprocessing site or on an adjacent site has been used; long-lived activity is limited in these disposals, so that the ultimate release of the site is feasible. Regular monitoring of water draining from such sites is carried out to demonstrate the continued safety of the procedure.

Another technique for the disposal of low-level solid waste which has been used by some countries is sea disposal, under carefully controlled conditions; the waste is placed in drums which are encased in concrete and dumped in selected known ocean areas in water at least 2700 m deep, often as a combined international operation, well away from fishing grounds.

The Dungeness B nuclear power station, on the Kent coast, during construction. Photo: UKAEA



Combustible waste has been incinerated at some sites, with special attention being paid to the cleansing of the gaseous combustion products by conventional scrubbing and filtering techniques. The resulting ash can either be subjected to chemical recovery treatment if this is economically feasible, or stored, economically because of its relatively small bulk. It is conceivable (and it is already technically possible) that extraction of longer-lived activity, such as that due to plutonium, from such ash could be undertaken to ease its ultimate safe disposal in the environment, even though the actual recovery of the plutonium was not itself economic. Medium-level solid wastes are generally stored long-term to allow their activity to decay, usually with a view to ultimate disposal by the most appropriate of the routes already mentioned.

... **Gaseous wastes** - The principal gaseous wastes in reprocessing arise as noted earlier from the shearing of oxide fuels, from the fuel dissolving operation and from the air used to ventilate such facilities as high activity liquid storage tanks. Particulate and entrained activity may be involved, as well as ^{131}I and ^{129}I and radioactive noble gases such as ^{85}Kr.

Invariably, fuel is cooled sufficiently before reprocessing to allow most of the short-lived ^{131}I (half-life 8 days) to decay, so this radionuclide rarely presents a significant problem. Particulate and entrained activity is kept to a low level by specially-designed gas-cleaning equipment including scrubbers and filters; in particular, a number of specifically developed absorption systems are used to trap radioiodine. Release to the environment is ultimately through high stacks fitted with monitoring equipment which registers activity levels and flow rates, so that activity levels in discharged gases may be known and recorded. As a final check at most reprocessing sites a programme of environmental monitoring is carried out in the area surrounding the plant - often extending for some miles around. The samples taken and examined include those indicative of potential public exposure, including radioiodine and radiostrontium in milk. The results of all these measurements are compared with derived working levels based on ICRP recommendations.

Two radionuclides have been studied especially in connection with their release in gaseous effluents: these are krypton-85 and iodine-129. The radiological effects, both local to the reprocessing site and on a worldwide basis, of the release of krypton-85 have been considered; the conclusion is that it will not pose a significant problem until well into the 21st century when, if steps are not taken for its removal and containment, the annual genetic dose from this radionuclide will probably approach 1% of the natural background level.

Methods of removing krypton-85 from the gaseous effluents from reprocessing are already technically feasible, and can be developed sufficiently against this time-scale to ensure that plants built after say about 1990 are equipped to remove and store this noble gas.

It has been established that iodine-129 would not pose a serious problem in gaseous wastes from a reprocessing plant serving a power programme of up to about 100 000 MW(e).

... **Liquid wastes** - There are three major categories of liquid wastes from reprocessing:

- **low level wastes**, such as fuel storage pond water, condensates from evaporators and many plant effluents;

- **medium activity wastes**, such as those arising from chemical decanning operations, and some plant effluents;

- **high activity waste**, containing the bulk (usually more than 99.9% of the fission products.

Large reprocessing plants produce several cubic metres of low level aqueous waste each day. After some treatment, which varies from simple storage to permit radioactive decay to sophisticated chemical processing, such waste is usually released to the sea or to rivers under carefully controlled conditions decided upon after many years of investigation. The generally accepted pattern for the research which precedes the determination of allowable releases to the environment is as follows: the composition of the waste (including likely variations) is established, the proposed release procedure is studied and the routes by which the radioactivity may return to man are found and quantified. In practice, one or two of these routes are normally found to be so limiting that if the resulting radiation exposure is kept within the dose limits recommended by the ICRP the total exposure from all other routes will be quite minor. This method of assessment and control of public exposure to radiation from waste disposal is known as the critical path approach. Examples of such possible critical pathways met in low level liquid waste disposal are:

- the concentration of radioruthenium in edible seaweeds
- the concentration of radiostrontium in fish

● the concentration of radiozinc in shellfish
● and the adsorption of radiozirconium on silt, which may lead to external radiation exposure of fishermen.

When the research and investigation phases have been completed the system becomes one of carefully measured releases within a specific and nationally laid down authorization, followed by systematic and appropriately widespread monitoring of the major critical exposure pathways. Usually this monitoring is carried out by the reprocessing facility operator, and independently by the national authorizing body responsible for environmental control.

One radioisotope is worth special mention in this discussion: tritium, formed during the fission process in the reactor. This tends to appear mainly in aqueous effluents from reprocessing as tritiated water. It is virtually impossible to remove tritium from aqueous waste streams by any reasonably economic method, and most of the tritium formed must therefore be discharged to the environment where it is readily diluted. Although the half-life of tritium - 12 years - is rather long, it is dispersed in the biosphere easily, and careful evaluation has shown that it presents no significant hazard to the public in the amounts in which it is released to the sea or to river systems from reprocessing plants. Nevertheless, measurements are invariably made both in discharges and subsequently, if possible, in the environment.

Medium activity wastes are very variable in composition but contain usually significant quantities of dissolved salts. They are treated by a selection or combination of methods such as evaporation (with transference of the concentrate to high activity storage), decay storage and chemical precipitation (with the settled floc being retained as a solid waste). The great bulk of such waste is thus transformed into low level liquid waste.

High activity waste: The bulk of the fission products generated in power reactors are contained in aqueous solutions of nitrate salts of various metals after reprocessing. The composition of the waste varies depending on the reagents used in the processing, and whether the fuel has been leached from the fuel cladding or whether cladding and fuel have been completely dissolved. Invariably the first stage in treatment is concentration by evaporation, but the degree of concentration varies considerably depending on the processing flowsheet used. If only small amounts of extra salts have been added and the cladding has not been dissolved, then a volume reduction to about 50 litres per tonne of uranium fuel is achieved, but in a number of plants 450-900 litres per tonne of uranium fuel processed result. This intensely active liquor is stored in thick walled steel tanks contained in concrete cells up to 1.5 m thick, themselves lined with steel; sometimes these tanks are underground. In order to remove the heat of the decay of the fission products cooling coils are incorporated in the tanks, and sometimes a means of keeping precipitated solids in suspension, such as air jets, is included.

Universally, sufficient spare tank capacity is retained to accept the contents of a leaking tank. Gaseous effluent from the storage tanks - mainly air used for agitating the liquid — is cleaned by specially designed gas cleaning devices such as scrubbers and electrostatic precipitators, and is monitored continuously as it is discharged from a high stack.

For a century or more the concentration of radionuclides in these wastes will be high enough to require their nearly absolute isolation from the human environment. During this time some of the shorter-lived radionuclides will decay, reducing the potential hazard of these wastes, but the concentrations of long-lived radionuclides such as ^{90}Sr predicate a total containment time of several hundred years. If the wastes contain substantial concentrations of transuranic elements such as ^{239}Pu the required containment times may range up to many thousands of years.

So far these wastes have been stored safely as liquids in tanks. Such storage is considered to be safe for many years to come, combined with surveillance and the use of the "spare tank" philosophy referred to above. But it is generally accepted that in due course some form of solidification of high activity wastes will have to be adopted for ultimate storage. A great deal of research on this topic has been carried out during the past 15 years in several countries, and several alternative systems have now been developed to a stage at which they could soon be adopted for transformation of liquid high activity waste into solid. Such solidification would make continued surveillance less vital, and would reduce requirements for the replacement of expensive tank storage facilities. But even if these wastes were to be solidified it is expected that interim storage as liquid would be required and, taking into account the projected continuing growth of nuclear power, that up to the year 2000 about one half of all high-level wastes generated would be in interim storage as liquid.

As mentioned at the beginning of this section, different processes give rise to rather different high activity liquid wastes, and certain solidification techniques which have been developed are more suited to some wastes than to others. Generally, all solidification processes involve heating the wastes to temperatures between 400°C and 1200°C, which drives off all the volatile constituents - mainly water and nitrates - leaving a calcined solid or a melt that cools to a solid. In most cases melt-making additives are included with the heated waste so that glass-like products result.

Ideally, the solidified wastes should have
- good thermal conductivity;
- low leachability;
- high chemical stability and radiation resistance, and
- mechanical strength

After solidification the wastes must be suitably contained. Interim storage of the solid on the site of the fuel reprocessing and waste solidification plant will probably be necessary to allow radioactive decay of most of the activity of radionuclides with short and intermediate half-lives. In order to dispose of the heat from radioactive decay the interim storage facilities will again need to be designed to provide cooling, using either air or water.

In some countries final disposal of the solidified waste in deep geologic formations such as salt mines is now being examined. Storage of the waste in carefully selected formations would ensure that they are not reached by circulating ground water during the time required for decay of their radioactivity to innocuous levels. Unless fuel reprocessing and waste solidification plants were located on the site of the formation used for disposal transportation of the waste would be necessary; as an alternative, the solidified wastes could be stored for long periods on the site of the fuel reprocessing and solidification plant in specially-constructed storage vaults.

The total risk associated with the management of radioactive wastes is the sum of the risks encountered in association with each step. The main goal is to reduce the cumulative risk to the lowest practicable level; as a result, the steps employed in waste management programmes may differ from country to country depending on the magnitude of the risks associated with each process used.

Transportation

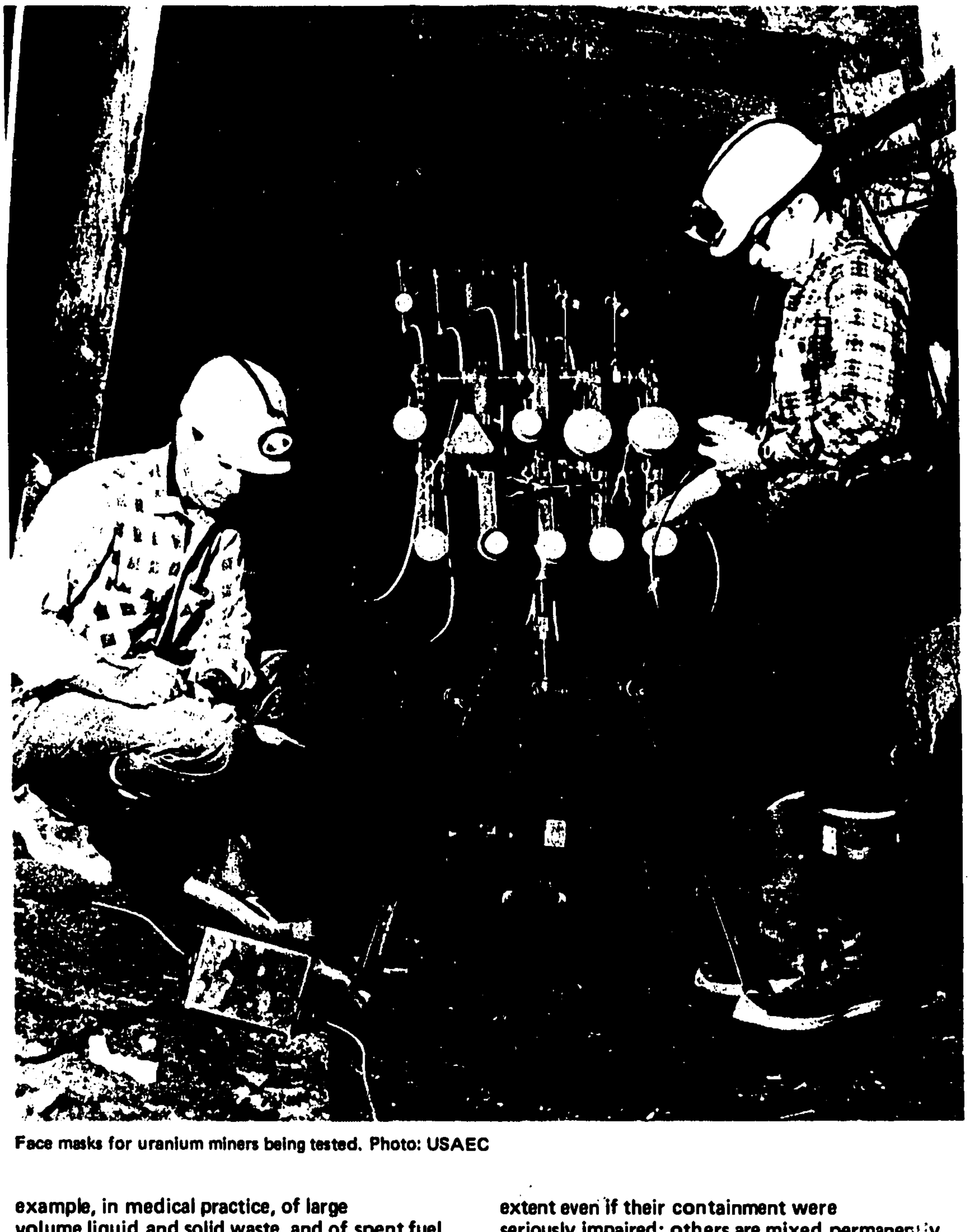
The safe and rapid transport of radioactive materials, whether in the form of unused or spent nuclear fuel, by-products or waste is a very important element in the development of nuclear power programmes. Great care is taken, through the use of trained workers and specialized equipment, to guarantee safety during the handling of radioactive materials; the standard of safety attained must be at least as high in transport, but the precautions taken should not be such as to hamper the free movement of consignments.

Suitably packed, radioactive materials are moved generally in normal conveyances by road or rail, in the air or by sea. They come usually into comparatively close proximity to the general public, and any release of the contents of packages may lead to contamination of the environment and of persons in the neighbourhood. The packages themselves will be handled in most cases by transport workers who have neither specialized training nor equipment.

Regulations must obviously be laid down to ensure that the packages are inherently safe, and that even in the event of serious accidents any escape of their contents which may occur would not lead to unacceptably high levels of contamination. It is also obviously desirable that the regulations of different countries should be as uniform as possible, so that packages can move freely from one country to another.

Soon after the IAEA was established it was recognised that this Agency was in a very favourable position to draw up regulations, applicable to all modes of transport, which could be accepted by national authorities and by organizations concerned with the international transport of goods. The Agency's regulations for the safe transport of radioactive materials were first published in 1961; they have been revised several times since. They have now been adopted as the basis of their own regulations by almost all international transport organizations, and are followed closely in the regulations laid down in many countries including those that are most heavily engaged in international trade in radioactive materials.

Potential hazards in transport are first the irradiation of persons or of sensitive substances such as photographic film which may result from insufficient or damaged shielding, and, secondly, the contamination of the environment and entry of contamination into the bodies of persons who happen to be nearby which may result from a failure of the containment. These potential hazards are associated to a greater or lesser extent with the transport of small quantities of radioisotopes used, for



Face masks for uranium miners being tested. Photo: USAEC

example, in medical practice, of large volume liquid and solid waste, and of spent fuel containing large quantities of fission products. Some radioactive substances are in the form of hard solids that would be unlikely to become dispersed in the environment to a significant extent even if their containment were seriously impaired; others are mixed permanently with a large mass of inactive material and can thus be considered to be of low specific activity. Some relaxation in requirements for the transport of such types of substances is permissible.

The root principle adopted is that the packaging itself should provide the necessary shielding and containment. It is not feasible to provide in all cases sufficient shielding to reduce external radiation levels to completely negligible values without adding excessive weight to the package. Three categories of package, identified by different labels, are specified in the regulations: for the first category the label is white with one red stripe, and the radiation level at any point on the surface does not exceed a value corresponding to 0.5 mrem/hour. For the second, the label is yellow with two red stripes; the radiation level at the surface of the package does not exceed values corresponding to 50 mrem/hour at the surface and 1.0 mrem/hour at one metre from the surface. For the third, the label is yellow with three red stripes; the radiation level does not exceed values corresponding to 200 mrem/hour at the surface and 10 mrem/hour at one metre from the surface. Each label also carries the trefoil symbol which indicates the presence of radioactive material. Neutron absorbers and spacers are built into the packaging for fissile materials in addition to the radiation shielding. In view of the safety features that are built in to packages for transporting fissile materials no special label is required other than those relating to the radioactive properties of the contents.

A large fraction of all consignments of radioactive materials contain relatively small quantities which would not present an unacceptable hazard even if the package containment were seriously impaired. It is therefore economic to prescribe two types of package in terms of containment standards; these are referred to as Type A and Type B.

Type A packages are designed to withstand normal transport conditions, including rough handling, without significant loss of shielding and containment. To be classified as Type A specimens of the packaging must pass a series of tests designed to simulate the effects that could be produced by weathering and expected rough handling. It is accepted that in an accident the containment may be impaired, and it is assumed with some experimental support that one-thousandth of the contents will escape and that one-thousandth of the amount that does escape may find its way into the bodies of persons nearby. An upper limit, based on its radiotoxicity and radiation emission, is therefore prescribed for the activity of each radionuclide that is to be transported in a Type A package.

Type B packages are designed to withstand very severe accidents without significant loss of shielding and containment. To be classified as Type B specimens of the packaging must pass both the Type A tests and additional tests including a 9 metre drop and exposure to fire, these simulating the conditions that might be associated with severe accidents in any mode of transport. The design of Type B packaging must be approved by the competent authority of the country in which it is produced. There is no regulatory upper limit to the activity that may be included in a Type B package, but the upper limit for the particular design is specified in the approval certificate of the competent authority.

Instructions issued to transport workers enable them to segregate packages of radioactive materials in such a way that the radiation levels in occupied places or near photographic film do not exceed acceptable values. These instructions are based on the information given on the package labels, and in particular on the radiation level at one metre from the surface [which is referred as to the transport index]. Additional requirements based on the transport index are specified for transport by rail, road, inland waterway craft, sea-going vessels and aircraft.

Accidents involving consignments of radioactive material have been reported on many occasions. Statistics for a wide range of countries are not available, but a report based on experience acquired in the United States has shown that on 146 occasions the radiological assistance plan was called upon in connection with accidents during transport involving radioisotopes. In some of these accidents relatively minor releases of radioactive contamination to the environment occurred. However, no release has been detected from any package designed to standards which approach the Type B specifications. This gives ground for some confidence that the Type B specifications will indeed ensure that a package will withstand very severe accidents without significant loss of its contents.

But it cannot be taken for granted that packages will always be properly loaded and assembled, and that accidents of unforeseen severity will never occur. Countries in which there is considerable traffic in radioactive materials have therefore set up systems which give some assurance that efforts will be made at the scene of an accident to prevent any avoidable spread of contamination, and that competent assistance in dealing with the accident will be given within the shortest possible time.

other impacts

The undertaking of any large-scale enterprise disturbs the environment. The production of electrical energy is no exception. Many of the disturbances which do occur are due not to the nature of the fuel used but arise from the normal processes of plant construction and ancillary operations.

Plant Construction

During the building of a large plant it may be necessary to provide new roads to allow access by vehicles used to transport construction materials to the site. The increase in traffic may impair the normal flow of traffic in the area to a considerable extent.

A site area of the order of 40 to 80 hectares (100 to 120 acres) is required for a 2000 MW(e) nuclear power station. Since good foundations are required to support the heavy weight of large structures it may be necessary to undertake a considerable amount of excavation and grading. These activities can increase considerably the amount of sediment which enters surface streams when it rains, and the amount of dust in the air during dry periods while the plant is being built.

The historical significance of the proposed site of a nuclear power plant, like that of any other kind of power plant, is considered carefully. Care is taken to minimize disturbance to any prehistoric petrified plants and animals or to any valuable archeological remains of early civilizations, graveyards, old buildings, ruins of walls, monuments, aqueducts and so on. Hydroelectric plants have associated with them large man-made lakes, which have replaced free-flowing rivers; fortunately, immense impoundments of water like these are not necessary to nuclear power plants. Often, alternative sites for power plants might be selected in order to avoid damage to or the destruction of natural treasures or priceless historic remains; if this is not possible intensive scientific investigations should be made before the plant is built, and the most valuable scientific and historic treasures removed to museums for safe keeping.

Transmission Lines

The overhead transmission lines associated with electricity generation and distribution have a highly visible impact on the environment. It is virtually impossible to conceal transmission line towers - pylons - and the lines themselves, but it is possible to do a great deal to make them less obtrusive and more attractive. The practices adopted obviously differ from country to country, because types of terrain and uses of land vary considerably; but in general transmission lines can be placed and oriented in such a way that they need not have a serious effect on the environment: they cannot be eliminated from the landscape, but they can be integrated into their surroundings. Cables laid underground might be an alternative in the long-run, but further development is required if this technique is to become practicable in economic terms.

Thermal Discharges

All steam-powered electrical generating plants, whether fired by fossil- or by nuclear fuel, have a common potential problem in their need to release unused heat to the environment. Recapitulating: heat from the combustion of fossil fuel or from the fission of nuclear fuel in a reactor is used to produce steam at high temperature and pressure, which drives a turbine connected to a generator. The 'spent' steam from the turbine is condensed by passing it through condensers cooled by large amounts of water. The heat transferred to the cooling water normally raises its temperature by a maximum of 5°-15°C under full load conditions. The discharge of this heated cooling water to aquatic systems is at the origin of the 'thermal effects' problem.

Comparison of thermal release from fossil-fuelled and nuclear plants

The reactors on the market at present operate at a lower efficiency than most modern fossil-fuelled plants of the same generating capacity. For this reason, and also because about 10% of the heat from fossil-fuelled plants is discharged directly into the atmosphere through the stack, nuclear plants reject about 50% more heat to the cooling water than fossil-fuelled plants. This difference should be reduced with the advanced reactors now being developed.

Nuclear plants on average use about 180 litres of cooling water per second per kilowatt hour, with an average maximum temperature rise across the condenser of about 10°C. Fossil-fuelled plants require about 115 to 150 litres per second per kilowatt-hour for a maximum temperature rise of about 8°C.

Cooling water sources and methods of heat disposal

Various constraints including economic and biological costs, aesthetics, statutes on water quality and cooling water sources govern the choice of the method of disposal of condenser cooling water. One of the most important factors is the type of source of cooling water available for a particular steam/electric plant. The body of water to be used may range from freshwater lakes and rivers to estuaries and coastal marine waters. In many countries or in parts of them there may be little choice but to use estuaries and coastal waters because there are insufficient lakes or rivers.

Basically there are three methods of disposal of heated discharges:

- by a closed-cycle cooling system;
- by a variable-cycle cooling water system;
- and by once-through operation.

In a closed-cycle system the condenser cooling water will flow from a condenser to an atmospheric heat exchanger (either a cooling tower or an artificial lake or pond) where it will lose heat before being returned to the condenser for re-use. In large steam/electric plants these systems are usually limited to freshwater sources, because when marine waters are used the drift of salt water may affect plant and animal life at considerable distances from the cooling towers. Two closed-cycle, hyperbolic natural draft salt water cooling towers have been used at the Fleetwood Station, a 90 MW(e) plant situated on the Irish Sea with minimal local effect; but for present-day large modern steam/electric plants (of, say, 1000 MW(e) or more) the use of salt water towers may not be desirable.

A variable-cycling cooling water system rejects some of the heat from the condenser cooling water in a cooling tower or flow-through cooling pond before discharge into a natural water body. Some of these systems are capable of operating at any point between the two extremes of closed-cycle and once-through operation.

When the supply of water is not a problem plants usually use the once-through system, in which the cooling water is taken from nearby rivers, lakes, estuaries or coastal waters and returned usually to the same source. Choice of the once-through method carries with it the need to select between several methods of minimizing the impact of thermal discharges upon a natural water body. These methods include the use of

- dilution in long discharge canals, using additional large-capacity pumps (to reduce the temperature of the cooling water by adding cooler water to it before it is discharged);
- jet and multiport diffusers;
- cold water from intake point deeper than the discharge point, thus using the naturally-cooler water available during the summer at these deeper points and reducing the temperature difference between the discharge water and the receiving water;
- and the release of cold water from upstream reservoirs.

Physical behaviour of heated discharges

Engineers and biologists are making considerable efforts to take into account the needs of both the aquatic biological community and the power plant in developing suitable designs for power plant cooling systems. Physical studies concerning water temperatures enable some predictions of temperature patterns resulting from heated discharges to be made. Information on temperature and behaviour of heated discharges is needed:

- to avoid recirculation of heated discharge waters, and thus to increase plant efficiency;
- to comply with regulations on water temperature standards;
- and to provide sufficient basic data to enable biologists and ecologists to assess thermal effects.

These thermal studies include mathematical simulation modelling, physical hydraulic modelling, and field studies at plant sites on lakes, rivers, reservoirs, estuaries and oceans. Their common goal is to assist in the designing of power plants in such a way that undesired environmental effects are minimized.

A plume formed by heated discharges can be considered to contain three regions: the near field, the joining region and the far field. In the near field, immediately adjacent to the outfall, entrainment of ambient fluid at the expense of the initial kinetic energy of the heated effluent is most important. From a biological point of view this region may be important because it is here that the highest temperatures are encountered, even though this region represents only a small fraction of the total volume of the plume.

The joining region is that in which entrainment becomes important together with buoyancy, advection and surface cooling. Differences in density of as little as 1% can lead to the formation of stable stratified flows in which momentum is transmitted easily to the lower regions, but transport of heat and matter is inhibited, as if by an elastic membrane, at the lower boundary of the plume. The principal mechanism by which temperature is reduced in this region is by lateral entrainment of surrounding fluid.

The far field is that portion of the plume where advection, entrainment and surface cooling dominate: momentum and buoyancy forces are no longer considered important. Of the three plume regions this is particularly amenable to analytical approaches; however, empirical values or relationships for the horizontal and vertical eddy diffusivities are required. The initial conditions for this regime must also be specified. Except in river and estuary situations physical boundaries need not be considered, since they would generally be remote to the plume.

Hydraulic modelling used to estimate the temperature and velocity distribution within a plume requires relations between the hydraulic model and a prototype. Exact modelling requires identically valued dimensionless numbers in the model and the prototype; in practice this is seldom achieved and several models must be used, each emphasizing separate considerations in order to produce the desired results.

The ultimate objective in the modelling of thermal plumes is to obtain spatial and temporal temperature and velocity distributions within the affected receiving water which, in turn, could be used to make biological and ecological predictions. The bodies of water receiving the discharge can be put into categories on the basis of their characteristics. Ponds are shallow and generally quiescent except for wind-driven flows. Lakes are larger and deeper than ponds and show stratification as well as current driven by winds. Larger lakes have internal currents. Rivers are characterized by undirectional flows with a velocity profile. Their flow volume shows short-term fluctuations due to weather as well as seasonal trends. In deep rivers some stratification is possible. Estuaries are characterized by cyclic flows due to tidal flushing, and stratification due to their salinity. Because of the cyclic movement recirculation of the heated water can be a problem. Oceans are characterized by good mixing due to currents and waves, and stratification due to temperature effects. Each of these receiving environments presents special design requirements and simplifications for analysis.

Thermal effects on biota and ecology

Perhaps no other single environmental factor affects aquatic life as profoundly or in such an all-pervasive manner as temperature. Unfavourable temperature may affect reproduction, growth, survival of larval forms, juveniles and adults, and all the life processes necessary to maintain a healthy state. A host of biological and ecological questions may be asked about possible damage to aquatic life in waters receiving heated discharges, and no reasonable person recommends uncontrolled release of heated water. Regulatory agencies at various levels of government are developing or have established water temperature standards which are used to govern heated discharges from steam/electric plants so that no catastrophic 'kills' or thermally-polluted waters or complete demise of desired aquatic populations are to be expected. If discharges of heated water are controlled then the primary concern is in 'monitoring' effects to make sure that no serious trends requiring corrective action are taking place on account of subtle temperature effects on populations, communities and ecosystems. Several pertinent problem areas in the thermal effects of nuclear power stations are reviewed briefly below.

Effects on fish - Disproportionate attention has been given to lethal temperatures for aquatic species, and not enough to the more subtle effects of sublethal temperatures on behaviour, reproduction, food web relationships, growth and other factors which may have a significant impact on the health of aquatic populations and communities. Nevertheless, for practical reasons one of the early tasks in planning for a nuclear power station is to assess the risks of direct temperature 'kills'.

The utilities give much attention to the prediction of the physical characteristics of the thermal plume from the discharge structure in order to avoid recirculation and to comply with temperature standards. This temperature data can give an early idea of the possible risks of thermal kills. In some cases the temperatures of the undiluted effluent are well below the published upper lethal temperature of the fishes of concern. In other cases the known avoidance behaviour of the fish

precludes the risk of thermal kills.
Comparison between the isotherms drawn for temperatures around the discharge structure and the upper lethal temperatures of the fishes of interest permits an estimate to be made of the size of the area in which the water temperature is potentially dangerous. But this comparison is only a grossly simplified examination of the thermal problem.

Animals and plants respond to the conditions in their total environment in a complex and integrated manner, although biologists often separate the various physical and biotic factors such as the effects of temperature for convenience. The response of marine organisms to the interaction of temperature, salinity and dissolved oxygen has demonstrated that a change in one environmental factor is influenced strongly by others. Lethal temperatures for a particular species are thus variable with acclimation, season, sex, age, physiological state, water chemistry and other factors. Predictions as to whether a particular water temperature in situ will kill a wild fish therefore need qualification, unless temperatures well above the ultimate, incipient lethal temperatures are being considered.

Reports of losses of aquatic organisms caused by natural or man-made temperature changes appear in the literature, but since these have been unexpected detailed measurements or observations are often lacking. Usually it is not known what other environmental stresses may have accompanied elevated temperatures. Reports on fish kills by heat should be evaluated cautiously with the various sources of error in mind, unless obvious, extreme, lethal temperatures were observed. Often these kills are reported without other water quality measurements taken at the time, and it is not uncommon to find that kills have been attributed to elevated temperature only to discover later that some toxic material or other environmental factor was actually the causative agent. Since heated discharges from a power station are common knowledge any dead fish found near a power station immediately renders the power station suspect. The loss of fish resulting from discharges of waste heat from steam/electric plants are not frequent, despite some expressed fears. By far the most fish deaths caused by pollution in the United States, for example, are the result of industrial operations - including the discharge of toxic materials and wastes from municipal sewage systems.

Many of the published lethal temperatures for freshwater and other marine organisms have been determined in the laboratory. Since such fish are not usually subject to other environmental stresses the published laboratory data must be treated cautiously if they are to be applied in the field. Nevertheless, in the absence of good data on the effects of heat on fishes in situ, laboratory data serve as good 'bench marks', or guidelines, although not as standards. To obtain data for direct application to a particular nuclear site perhaps the most meaningful approach before the plant begins operation is to test the desired species in heated water on site, realizing at the same time that the biologically-important relationship to be investigated is the temperature-time exposure history. The discharge structures of many existing power plants provide for rapid reduction of the temperature in the thermal plume by dilution. Therefore the determination of the sublethal and behavioural effects of short-term exposures on the desired species are most applicable. The tolerance to acute lethal temperatures must be defined at each site; however, in the temperate regions proper siting and design can generally maintain discharge temperatures below acute limits. [The thermal effects problem tends to be less acute in temperate waters than in tropical waters largely because the ambient water temperatures are further from the lethal temperatures of aquatic species.]

The avoidance behaviour of fishes observed both in the laboratory and in field studies is an important factor often overlooked by those concerned about thermal fish kills. The general lack of fish kills at several existing nuclear power stations depends to a large extent on the ability of certain desired fishes to avoid lethal temperatures successfully. Clearly, if the undiluted effluent temperature is in the lethal range this should be cause for concern; but this does not necessarily mean that the risks of thermal kills are high. Proper design of outfall structures and an understanding of fish behaviour in response to temperature gradients are important factors tending to minimize risks. No thermal kills of fish would be expected even if there were small areas of lethal temperature, if the fish did not experience high temperatures for extended periods of time.

While many fish demonstrate avoidance behaviour in response to lethal temperatures, fish also tend to congregate about their preferred temperature. It is interesting to note that thermal history or acclimation has a positive correlation with the preferred temperature in some species but no effect on others. The congregation of fish in the warmer waters of the discharge canals during the cool season has commonly been observed at steam/electric plants. The question whether the warmer waters are actually beneficial to production and health of desired fish needs to be investigated. It can be stated, however, that in many cases the congregation of desired fish is beneficial to sportsmen, since the availability of fish is increased.

Effects on plankton - There are many ways of assessing the effects of heated discharges on plankton. From a basic biological and ecological aspect, biologists may be concerned fundamentally with the same types of thermal thermal effects discussed for fishes, although plankton represent a lower trophic level. Interest is mainly in how heated discharges affect the metabolism, physiology, growth, reproduction, population dynamics and other life processes of planktonic species.

Plankton, especially in the marine and estuarine environments, present a much more difficult problem. Relatively little is known about the population dynamics of even one planktonic species, let alone the numerous species represented in any body of water. Generally the task of proper identification and sampling is much more difficult for plankton than for fishes. Of course, it is elementary that plankton are important in an ecosystem in their own right, but they also form the important and essential food base for many shell- and food fishes.

Further studies are needed. But we are faced with a pressing need to make some early assessment of the effects of heated discharges from nuclear power stations. Investigators working on the problem appear to use two approaches, namely, estimates of kills of plankton entrained in the condenser cooling system, and estimates of the kill in the receiving water body.

The significance of plankton killed by a power plant may often be difficult to assess in terms of the effect of the kill on the health of the planktonic population as a whole. After all, many pelagic fish larvae suffer greater than 99.99% natural mortality. It would seem that any large effort expended to answer questions concerning the impact of plankton kills by towing plankton nets may be spent more effectively in other research areas. For example, if there are indications that significant numbers of clam larvae are killed then an extensive study of the dynamics of the local clam population being harvested seems to be practical. If important food organisms for desired fish are being killed a study of the growth, gut-contents and health of the desired fish population might be undertaken. Other approaches and methods might be used; but the point here is that while plankton studies are needed they should be kept in proportion with the total support available for research, and the objectives of the project.

Effects on benthos - Since the temperature of the effluent from a nuclear power station is not 'boiling' hot but averages about 10°C above the ambient temperature, the receiving water near a shoreline outfall will not be devoid of aquatic life. Nevertheless, the diversity of the benthic flora and fauna near the influence of the heated discharges would be expected to change. But we have limited knowledge, especially in the marine or estuarine environment, and it is therefore extremely difficult to assess or to predict in the long-term the effect of these changes.

The bottom organisms resident in the area of influence of heated discharges are generally considered to be good indicator organisms for thermal effects. Since macroinvertebrates, rooted plants, and macro-algae are essentially non-mobile - unlike free-swimming fish - these bottom organisms may be exposed to heated discharges continuously. Partly for this reason, most ecological surveys for nuclear sites include bottom samples in the pre- and post-operational studies.

It is frequently suggested that heated discharges may destroy bottom organisms which are important food organisms for fishes. It is then often implied, if not stated explicitly, that the populations of desired fishes will suffer great harm since fish obviously depend upon lower trophic levels for food for successful growth and reproduction. The concept of the food supply being one limiting factor for a particular fish population is not unsound, but a search of the literature on field experiences shows no good example in which a heated discharge destroyed benthic organisms to such a large extent that its impact was reflected in the health of the desired fish populations.

It is common experience that the original bottom organisms inhabiting the environs of the shoreline outfall of a nuclear power station are usually lost due to the scouring action of the discharged water, which changes the bottom characteristics. Casual observations often attribute this loss erroneously to heat; but observations made on the effects of the velocity of discharge water on benthic organisms before plant operation confirm that the loss occurred before heat was added. The bottom area affected by the changed water current is usually relatively small, and should have no significant impact.

The environment of a power station site must be examined in detail both before and when a station is in operation to determine the effects arising from its operation. Extensive and continuing ecological studies have shown that the discharge of heat from power stations can be planned and made without causing large-scale changes in the environment, any changes observed so far being local to the point of discharge.

Both in rivers and in estuaries discharges are being made at the present time which do not in any way hinder the migration of fish past the stations concerned. Moreover, current interest in the possibilities of commercial fish-farming, using warm water from power stations to improve the rate of growth of the fish, is an indication that positive benefit may be obtained from heating – rather than the reverse.

public health considerations

Some critics advocate stoppage or substantial reduction in the growth of power programmes, out of concern for their impact on natural surroundings. Although such stoppage or reduction might be justifiable in some local contexts, in the wider sense and viewed from a public health standpoint they cannot be considered to offer a universal solution. Just how much people are dependent on energy becomes evident whenever there is difficulty in obtaining conventional fuel supplies, as occurred recently in the United Kingdom and in the north-east of the United States. In the public health sense the obligation is not really to deny people energy out of concern for their environment, but to harness energy for man's overall good. Energy use is linked too closely with jobs, and the disposal of wastes with health and security, mobility and comfort, to be put second to the preservation of a totally undisturbed natural world. What must be found is an appropriate balance between the socio-economic aspirations of man, and the amount of disturbance of his environment which he is willing to accept in attaining his goals. Systematic and deliberate planning for the best use of available resources is necessary in order that the public interest be best served.

Nuclear Power Generation

The aspects of nuclear power production which have key implications for the public health are:

- low level radioactive releases
- thermal effects of waste heat
- long-lived radioactive waste residues
- and possible accidents and their mitigation.

These can perhaps be best discussed in the context of an examination of the fuel cycle, keeping in mind the origins and relative amounts of radioactive wastes and waste heat described in Chapter III.

Mining

As indicated previously, the underground mining of uranium can expose the miner to dust containing naturally-occurring radionuclides. These dusts, together with radon (a radioactive gas formed by the decay of radium in the ore), pose an occupational hazard to the miner. More specifically, miners can be exposed to daughter products of radon-222 (which is a daughter product of ^{226}Ra, which in turn is a daughter of natural uranium).

Before the development of current practices, which reduce the exposure of miners, over-exposures were experienced and a number of deaths due to lung cancers resulted. During the past 20 years more than 100 uranium miners have died of lung cancer in the United States, and it has been estimated that 500 to 1500 miners who were exposed prior to the establishment of present-day occupational safety standards may die similarly of radiation-related disease.

The ICRP recommended in 1959 a limit of 3×10^{-8} μCi of ^{222}Rn per millilitre as a maximum permissible concentration (assuming 100% equilibrium with daughter products and 10% of Radium-A ions unattached). National working standards have been established based on this recommendation. [In the United States a working level (WL) corresponds to any combination of radon daughters in one litre of air that will result in the emission of 1.3×10^5 MeV of potential alpha energy. The numerical value of the WL is derived from the alpha energy released by the total decay of the short-lived daughter products in equilibrium with 10^{-7} μCi of ^{222}Rn per ml in air. The limit for exposure in US mines is four months at working level per year.] This subject has been discussed by the ICRP for several years, but no evidence has been presented to suggest that the 1959 recommendations should be changed.

From the viewpoint of public health several factors must be borne in mind:

- Radiation exposures of the lungs of miners before national standards were established on the basis of ICRP recommendations are not known precisely, but they have been estimated as being several thousand times higher than the present exposure limits.

● Many studies have indicated that cigarette smoking by the miners greatly increased their risk of contracting lung cancer, though exposure to the daughter products of ^{222}Rn is the primary factor implicated.

● By keeping working conditions well within limits established by the ICRP the risks of lung disorders in uranium miners should be far less than those experienced in the mining of other materials.

● The establishment of safe working conditions in uranium mines requires the efficient ventilation of mine galleries to remove radon and its daughter products. The radon exhausted from the mine is rapidly diluted by diffusion in the atmosphere, and does not give rise to problems of public exposure in the surroundings of the mine.

Milling, enrichment and fuel fabrication

The piles of tailings from milling operations give rise to several possibilities of difficulty away from the site in assuring public health. If strong winds and dry conditions are common it may be necessary to stabilize the piles in some way to prevent the transport of dust clouds to populated areas. If the piles are exposed to weathering and to water leaching attention must be given to the water runoffs, as they are likely to contain radium. The trend at present is toward storage of tailings within dry mines, or in other protected geologic formations.

Historically, tailings have sometimes been used in road making and as backfill in building construction. Uses such as these, especially when coupled with the use of building materials that themselves contain high levels of naturally-occurring radionuclides, can result in inadvertent increases in radiation levels compared with the normal background. Prudent practice — in keeping with the ICRP philosophy that the radiation exposures received by the public should be kept as low as possible — discourages uses of tailings such as those described.

Uranium ore concentrate from the mills is refined and converted to UF_6 for enrichment in gaseous diffusion plants. The chemical processes involved, the process control standards invoked and the safety procedures instituted in fuel fabrication and gaseous diffusion plants are such as to preclude essentially any toxicological or radiological impact on individual members of the public (except the radiation workers actually involved) or the population as a whole. Additionally, the strict accounting requirements which attend the processing of fissionable materials in countries engaged in the production of nuclear fuels gives added assurance that discharges of gaseous and/or liquid effluents contaminated with slightly-enriched uranium are so small as to be negligible.

When fuels are fabricated only from uranium, with no recycling of fissile materials obtained from reprocessed fuels, no important environmental problems arise: the necessity for good conditions of work for the personnel involved is generally sufficient to guarantee that contamination is confined within the plant. In the near future, however, plutonium oxide fuels will be fabricated for breeder reactors. Plutonium, because of its very low MPC, must be handled and processed using very stringent precautions to protect operational personnel; this implies working in specially equipped and confined workshops, but in normal operation creates little risk to the public. Nevertheless, attention must be given to accidental situations at the installation — especially those involving fires, which could lead to the destruction of filtering devices and permit the escape of important quantities of plutonium.

Reactors

Siting - The selection of a site for a nuclear power station involves the same basic considerations as any other power plant project with respect to proximity to load centres, transmission routes and accesses, waste heat disposal possibilities and other, economic factors. The unique feature of the nuclear plant stems from the radiological implications of the fission product inventory formed in the core. Operating experience with nuclear power stations so far has been that in most cases plant effluents contain such low levels of radioactivity as to be barely perceptible, if at all, above the natural background in areas off the sites themselves. Considerations of radiation exposure of persons in the vicinity of plants from normal effluents does influence plant design and operation, but in general they do not affect significantly the location of such plants. People can live more safely next to the boundaries of the site of a nuclear power station in normal operation than they can near many conventional industrial complexes.

Why, then, have reactors generally been removed from the immediate vicinity of large numbers of people? The answer lies usually in concern about the remote possibility of a major accident in which the containment of radioactivity could be breached. Such an accident has a very low probability of occurrence and, as discussed in Chapter III, engineered safety features have been developed to limit the release of radionuclides from a nuclear plant should any take place. Nevertheless, a conservative approach has been used in the siting of such facilities.

All nuclear power stations are designed to contain abnormal events safely, but emergency plans are always established for each installation in case any abnormal release of radioactive material occurs. Although designs differ – and the requirements laid down by various national authorities do vary in the individual weightings given to certain remote possibilities – there is universal recognition that the possibility of accident is dominant in assuring the safety of the plant. Siting is one of the aspects of plant design that is so influenced.

No fixed distance from living areas is universally applied in deciding upon the siting of nuclear installations. The distance at which a plant is built from a substantial population group varies considerably between countries, and from one plant to another within any one country. This variability results from the interplay of site characteristics with both the inherent safety features of individual designs, and the safety features engineered into them to cater for a wide range of abnormal possibilities. There is, however, a commonness in siting which might be characterized as follows:

- Site selection involves an integrated consideration of site characteristics and the safety features of the facility concerned.
- Facilities are designed and operated in such a way that they comply with radiation protection guides which admonish the responsible authorities to keep radiation doses as low as is practicable, and in any case within nationally-prescribed upper limits.
- Facilities are designed in such a way that accidents that could result in meltdown and dispersal of the fuel are prevented or made highly improbable.
- The low probability of fuel meltdown notwithstanding, the authorities require that in the interests of public safety and environmental protection nuclear plants are capable of confining any significant effects of an accident of this type to the plant or its near vicinity.

Normal operations – As discussed in Chapter II, experience has shown that it is possible to generate nuclear power while limiting offsite effects of radioactive effluents in the vicinity of plants to very small increases in background radiation levels.

The very small amounts of radioactivity which are released to the environment include tritium and radioisotopes of iodine, krypton, xenon and sometimes carbon.

Most of the tritium and gaseous fission products are retained in the fuel elements until they are reprocessed, and their behaviour will be discussed later in a section dealing with fuel reprocessing. Carbon-14, however, may be produced and released at the reaction station. The main contribution to ^{14}C production is neutron irradiation of ^{14}N which may be used for sparging in a reactor.

Carbon is the structural base for all organic material, and plays a significant rôle in all forms of life. The half-life of ^{14}C is quite long – more than 5500 years – so when it enters the environment it becomes incorporated into the carbon cycle and thus penetrates every living organism.

Nuclear weapons tests resulted in a near doubling of the amount of ^{14}C in the atmosphere during the years 1962-63. Since the cessation of major testing programmes the excess amount of ^{14}C in the atmosphere has gradually decreased, and is expected to drop to about 3% of the natural amount by the year 2000.

The amount of ^{14}C entering the atmosphere from nuclear power stations is expected to increase continuously during the next several decades. Depending upon the rate at which atmospheric ^{14}C cycles into other compartments of the environment, its level may become high enough to warrant serious attention.

However, the increase in radiation levels in the environment which results from the release of this and other radionuclides cannot usually be distinguished from the background. The radiation exposures of population groups from reactors are considerably less than their exposures from other sources – such as medical diagnostic procedures – and are well below the limits suggested as maxima by national and international radiation protection advisory bodies.

... Accidental events

Experience acquired in many countries in the safe operation of a number of different types of power reactors has been impressive and encouraging and the abnormal events that have occurred have not jeopardized public safety. Nevertheless, the sum total of the experience that has been acquired is still quite limited, and it cannot be said that the probability of an accident serious enough to have consequences offsite is zero.

Many assessments of the potential consequences of postulated accidents involving the release of radioactive materials beyond the site boundary have been made. In this context a number of things should be said:

– Reactors cannot explode like atomic bombs. Neither the composition of the fuel nor its physical configuration permit this to happen.

[It is sometimes falsely implied that they can by people who observe that a reactor can contain a fission product inventory comparable in radioactivity to that created by the detonation of a nuclear weapon.]

– The occurrence of significant offsite effects would require extremely unusual initiating events, coupled with failure of multiple safety devices provided to protect the public against such possibilities.

– The probability of accidents having serious offsite effects is generally believed to be so low as to approach zero. Although they are not quantifiable, the risks of harmful public exposures are judged to be much lower than those of natural events such as earthquakes, floods and lightning. If a serious reactor accident were to take place – one might be faced with quite serious contamination of property and even loss of life.

Governmental authorities require generally that emergency plans be prepared in advance to cope with situations such as a reactor accident. The main measures to be taken include:

- rapid survey to delineate the direction and extent of the plume of released radioactivity;
- warnings to and instruction of the population;
- restrictions on the movement of people, the consumption of milk, water and food from contaminated areas, and so on;
- prevention (if possible) of the extension of the accident;
- and survey of and medical assistance to irradiated persons.

. . . Thermal aspects

As discussed in detail in Chapter IV, the need to cool the condenser of power plants, whether they are fossil- or nuclear-fuelled, results in the rejection of waste heat to the environment. The growth of electricity production is thus heavily dependent upon access to sources of cooling water. Where populations are comparatively concentrated this growth can lead to competing demands upon water resources – those of the power station, and from others for recreation, fishing, scenic preservation, irrigation and public consumption. It does not appear that the growth of the electricity supply industry is being limited unduly by constraints upon water availability, but the choices for sites are being narrowed, and the engineering community is being pressed for innovative solutions which will minimize the impact of power generation on water bodies.

Whether the addition of heated water to the receiving waters can be assimilated without significant effects is dependent upon various factors such as the manner in which the heated water is returned to its source, the temperature and amount of source water available, and the aquatic biota present in it. There is no doubt that this waste heat can be detrimental in some cases, but it does not follow that it must be. Each system must be examined on its own merits.

Alternatives to the "once-through" cooling system are being developed in a number of countries for use when there is an inadequate supply of cooling water. These involve the use of artificially-created lakes or ponds, or the erection of cooling towers. Although these alternatives may offer relief from the addition of large amounts of waste heat to natural bodies of receiving waters, their use can have other environmental effects and economic penalties. For example, each of the methods mentioned results in a higher consumption of water than a once-through system. Cooling towers add large amounts of water to the atmosphere and this can result, under certain conditions, in fog, ice formation on trees, roads and transmission lines or snow. Chemicals including chlorine, zinc, chromium and phosphates are added to the water in cooling towers to inhibit the growth of organisms within them, corrosion and the deposition of dissolved salts. These chemicals, transported in tower plumes (spray drift) and in tower blowdown, may have damaging effects on the environment. In addition, cooling towers – especially hyperbolic natural draft cooling towers – can pose aesthetic problems in some cases.

Artificial lakes or cooling ponds may relieve thermal effects in natural bodies of water, and may also be used for recreation and other purposes. But they can be used only if enough land is available: 2000 to 3000 acres of lake surface are required for a 1000 MW(e) nuclear power station. Whatever metod of cooling is chosen, the waste heat from both fossil and nuclear plants must still, eventually, be dissipated in the environment.

. . . Chemical aspects

Normal operation of a nuclear power plant requires the discharge of certain chemicals from the turbine condenser cooling system, the radioactive waste system, the regeneration of process water demineralizers, the laundry waste system and the sanitary waste system. The chemical content of the discharge from these systems will vary from plant to plant.
For example, chlorine or some other biocide may be added intermittently to cooling water to remove accumulations of organic matter inside the condensers; phosphate and zinc

compounds may be used as corrosion inhibitors; sulphuric acid may be used to adjust the alkalinity of recirculating cooling water; and demineralizers may be regenerated periodically with sulphuric acid and sodium hydroxide, the regenerants then being neutralized before discharge. The maximum concentrations of some of these chemicals in the discharge canal could conceivably exceed levels which are toxic to aquatic life. Temperature, as the "master factor" affecting rates of all metabolic functions, can influence the speed with which toxic substances exert their effects and, in some instances, can influence the threshold concentrations for toxicity.

The technical assessment of the potential impacts of chemical and sanitary wastes from nuclear plants is included in the environmental evaluation made in the early stages of planning. The sources of potential biological damage considered include: moisture from cooling tower plumes and airborne spray drift; chemicals from tower blowdown; chemicals from airborne spray drift on surrounding land and vegetation; and chemicals such as chlorine that may be toxic to aquatic life. Assessments such as these guide those who must supply solutions to meet water quality standards.

Fuel reprocessing

As discussed in Chapter III, the major radioactive wastes which have some public health in implications and which arise in the course of normal fuel reprocessing operations can be broadly categorized according to their physical state and activity level.

The management of these wastes is governed broadly by the application of three widely-accepted principles:

- **dilute and disperse** for low-level liquid and gaseous wastes;
- **delay and decay** for intermediate- and high-level liquid and gaseous wastes, particularly those waste streams that contain short-lived radionuclides; and
- **concentrate and contain** the intermediate- and high-level solid, liquid and gaseous wastes.

It is not always easy to apply one principle in preference to the other two, therefore some combination of the three is often followed. The nature and volume of the waste, limitations of the site for safe disposal, possible radiation risk to nearby populations stemming from release to the environment and cost are taken into account.

The principle of dilution and dispersion is based on the assumption that the environment has a finite capacity for dilution of radionuclides to an innocuous level. The application of this principle requires an understanding of the behaviour of radioactive materials in the environment and of the pathways by which the released radionuclides, particularly those that are considered to be critical, may lead later to the exposure of man. A large body of knowledge is available for use in the application of this principle, especially in meteorology, geology, geography, hydrology, hydrography, oceanography, ecology, soil science and environmental engineering. Applications of this principle have been made cautiously, thus ensuring that the releases are minimal and in any case are well within the capacity of the total environment to receive them.

The second of the three principles is rooted in the fact that radionuclides lose their radioactivity through decay. It may be called upon in the treatment not only of intermediate- and high-level liquid and gaseous wastes but in some cases also in that of low-level wastes. The intent is to ease problems in subsequent handling or to lessen risks of releases to the environment, taking advantage of the decay of some radionuclides — particularly those having short half-lives — with the passage of time. If high-level waste is held in storage in a liquid form the risk of accidental release might dictate in some circumstances early conversion to solid form.

The principle of concentration and containment derives from the concept that the majority of the radioactivity generated in the production of nuclear power must be kept in isolation from the human environment. Since some radionuclides take a long time to decay to innocuous levels some wastes must be contained for extended periods.

This principle is invoked in techniques for air and gas cleaning; the treatment of liquid wastes by scavenging and precipitation, ion exchange and evaporation; the treatment of low-level, solid wastes by incineration, baling and packaging; the treatment of intermediate-level solid and liquid wastes by insolubilization in asphalt; conversion of high-level liquid wastes to insoluble solids by high-temperature calcination or incorporation in glass; tank storage of intermediate- and high-level liquid wastes; storage of solid wastes in vaults or caverns; and disposal of solid and liquid wastes in deep geological formations.

Experience in the application of these three principles which has been gained so far has been that the various wastes arising within the nuclear fuel cycle have been controlled adequately with respect to both public health and the minimizing of environmental contamination. But, in the light of the expected expansion of the nuclear power industry as a whole, it is important that the responsible agencies improve continually their surveillance techniques, review waste management practices in the industry, and evaluate their potential impacts on the public health and on the environment.

Special mention should be made of four aspects of the management of radioactive wastes which have been the subject of considerable investigation and which call for some continued supervision. In some cases further technological innovation at reprocessing plant sites may be needed in future. These aspects are:

- release of the noble gas fission product krypton-85;
- release of tritium;
- release of iodine isotopes;
- and storage of highly active fission product waste.

... Release of krypton-85

The health interest in this nuclide, which has a half-life of 10 years, is primarily in the whole body dose the public at large may receive from it after its global dispersion. Locally, the concern is with the skin dose. Although krypton is slightly soluble in body fluids, and even more soluble in fatty tissue, it does not enter the metabolism, so does not concentrate in any particular organ.

The rate of discharge of krypton-85 will increase roughly in proportion to the overall size of the nuclear power programme; but a recent authoritative assessment, which projected the growth of nuclear power to the turn of the century, concludes that national and world-wide radiation doses would not be likely to pose any significant problems. It was estimated that in the year 2000 the annual genetic dose from krypton-85 would approach 1% of the natural background dose rate. Processes now being developed could be ready to extract noble gases from the gaseous effluent from reprocessing plants when the need arises. Some claim it would be prudent to make provision for the later addition of such removal equipment in any reprocessing plant built after about 1990. The long-term storage of the extracted krypton-85 should not pose insuperable technical problems; however, one needs to bear in mind that this approach would entail the substitution of a concentrated source of ^{85}Kr at a repository, with attendant risk of accidental release of large quantities, in contrast to continuous dilution and dispersion from a number of distributed sources. A careful risk/benefit assessment should be made before one course is chosen in preference to another.

... Release of tritium

The health interest in tritium, which has a half-life of 12 years, is again in whole body dose. Most tritium is released as tritiated water and becomes rapidly diluted and dispersed in the circulating waters of the world. The discharge rate of tritium will also increase roughly in proportion to the size of the power programme. Several recent careful assessments, however, conclude that the quantities of tritium likely to be released present no significant hazard to the public. For example, it is estimated that by the year 2000 — assuming that the present rate of growth of the nuclear power programme continues — the accumulation of fission product tritium will be about 700 Megacuries. Tritium is produced naturally, by the bombardment of nitrogen in the upper atmosphere with cosmic rays, at a rate of about 4 to 8 Megacuries a year, giving a steady state inventory of natural tritium of between about 70 and 140 Megacuries. It is estimated that 1700 Megacuries of tritium were released to the atmosphere as a result of the large-scale testing of thermonuclear weapons. It is therefore expected that for the next two decades most tritium in the environment will be that which resulted from nuclear weapons testing, and that the total inventory will decline during this period. The average annual whole-body dose from tritium is estimated to be of the order of 0.001 millirem for each 100 Megacuries of the total inventory.

... Release of iodine isotopes

Iodine isotopes are of significance to public health because their release is followed by a comparatively quick transport back to man along the pathway grass — cow — milk — human thyroid. The dose to the thyroid is the most important, especially for children because they tend to consume larger quantities of milk and their thyroids are considered to be more radiosensitive than those of adults. Iodine-131 is of particular concern in the accident situation because of its behaviour in the environment.

As mentioned in Chapter III, fuels from thermal nuclear power stations are normally cooled for periods of the order of 100 days before reprocessing, so that iodine-131 (8 day half-life) largely decays during storage and its subsequent release during decanning and reprocessing is extremely small. Most of the iodine appears in the low-level aqueous wastes, and a small fraction passes to the atmosphere through the conventional, moderately efficient alkali scrubbing system; in each case the release is well within the derived working limits. In future, when fuel from fast reactors is reprocessed, the economic incentive for a rapid turnaround in the fuel cycle may prompt the reprocessing of fuel which has been cooled for a shorter time. This will pose problems in providing new and very reliable techniques for the removal of iodine-131 from both gaseous and liquid effluents. Development work on fuel transport, off-loading and reprocessing itself will be required; removal of iodine at an early stage may be desirable.

A recent assessment touching on gaseous and liquid wastes from thermal or fast reactor fuel reprocessing has shown that releases of iodine-129 (7 million year half-life) are likely to be maintained well within derived working limits for this nuclide.

... Storage of high activity fission product waste

Fission product waste, containing traces of plutonium and of other transuranium elements, is so concentrated and contains nuclides with such long half-lives that it must be kept isolated from the human environment for hundreds or even thousands of years. The management of this waste at the reprocessing plant and during eventual storage in some man-made repository must recognise its great potential impact on man and his environment, and be the subject of continuing attention and development.

Whether the waste is stored for all time as liquid, or is converted ultimately to a solid form for storage, the major public health concern is preservation of containment.

It is probably easier from this point of view to demonstrate the overall safety of solid storage in deep natural vaults than that of liquid storage; the need for continued burdensome surveillance is much reduced and the removal of the waste from proximity to man's environment is attractive. But the hazardous aspects of the process of solidification must be borne in mind, together with the fact that an initial period of storage as liquid is still required.

... Accident considerations

The previous section discusses public health aspects of normal operations in a fuel reprocessing plant. Brief consideration will now be given to accident conditions which might affect public health or have other implications for protection of the environment.

The basic chemical operation of a reprocessing plant is, in theory, rather like that of similar industrial chemical processing operations with regard to the possibility of accident. However, in the design of a fuel reprocessing plant and in the development of flowsheets for its operation great care is taken to avoid creating the hazard of releasing radioactive materials. For example, the use of low-flashpoint flammable solvents or of gas compositions which may explode is normally excluded. The whole design of the plant with respect to shielding, containment, ventilation with discharge through absolute filter systems, in addition to protecting the operators, means that incidents which may occur will tend to be isolated within it.

Fuel dis-assembly, decanning and dissolving can conceivably present a small fire risk in some unusual circumstances. Such incidents will not result in significant environmental contamination because air extracted from the cells in which these processes are carried out is filtered efficiently. Subsequent chemical reprocessing carries with it small risks of fire, explosion or criticality incidents, but again scrubbing and filtration of the exhaust air will keep environmental contamination to low levels, and render the problem one of protection of plant personnel rather than of public health.

The most serious problem would be loss of containment in the high activity storage unit. The risk to the public of this type of event is minimized by the adoption of the "spare tank" philosophy (so that material can be transferred rapidly from a leaking tank) and by the siting, exceptionally high standards of construction of and vigilant surveillance over the storage unit. Solidification would reduce the mobility of these wastes, and a further reduction in mobility could be achieved by burying the solids at levels below which circulation of water takes place.

Transportation

Elements of the nuclear fuel cycle — mines, enrichment plants, power stations and so on — will be spread over large geographic areas, with some installations possibly in common for groups of states. This renders the problem of

Table IX.
Shipment Statistics for Elements of the Fuel Cycle in the United States

	Number of Shipments	
	1971	1974
Mill → Converter (as U_3O_8)	704	1071
Converter → Enrichment Plant (as UF_6)	938	1438
Enrichment Plant → Powder and Pellet Mfgrs. (as enriched UF_6)	781	1347
Powder and Pellet Mfrs. → Fabricators (as enriched U_3O_8 powder or pellets)	136	223
Fuel Fabricators → Reactors (as fuel elements)	272	360
Reactors → Spent Fuel Reprocessing (as spent fuel elements)	76	1417

transportation of nuclear materials crucial to the maintenance of safety and good economic performance of nuclear power systems. As an example, Table IX shows the number of different types of shipments in the nuclear fuel cycle in the United States which were made in 1971 and are expected to be made in 1974.

Nuclear fuel for a 1000 MW(e) reactor consists typically of about 90 metric tons (90 000 kg) of slightly enriched uranium. The fuel is in the form of elements made up of tens to hundreds of stainless steel or zircaloy clad fuel rods. About one-third of the fuel elements are replaced each year.

The radioactivity of new, unirradiated reactor fuel is small, about 3 curies per metric ton. This amount of radioactivity can have essentially no impact on the environment, and very little on individual transport workers under normal conditions. Even in an accident (except in the case of accidental criticality) the physical properties and the low specific activity of the fuel would limit radiation effects to very small levels. Although the packaging is designed to prevent accidental criticality under normal and severe accident conditions there is a very small probability that accidental criticality could occur. If it did, radiation doses in excess of 500 rems to individuals in the immediate vicinity might result, and the immediate area would require a thorough and perhaps costly decontamination.

Irradiated fuel elements contain large amounts of radioactivity generated by fission products which decay rapidly during the first few days out of the reactor. After 150 days each irradiated fuel element can still contain millions of curies of radioactivity, producing high radiation fields in its vicinity. For shipment, irradiated fuel elements are placed in shielded, air- or water-cooled casks weighing from 23 000 to 68 000 kg or more. Under normal conditions certain transport workers — truck drivers, train brakeman, barge operators and so on — could receive significant radiation exposures, especially if they are handling a number of shipments each year, and have to be treated as radiation workers; but members of the public should not exposed. Impacts on the public and on the environment as a consequence of accidents during shipment of irradiated fuels involving, for example, leakage of contaminated coolant, loss of coolant as a result of major damage to the cask, damage from severe impact and fire could be severe in terms of population dose. But no such accident has occurred so far and elaborate precautions as outlined in Chapter III are taken to prevent their occurrence.

Under normal conditions the shipment of drums of waste from a nuclear plant should have little radiological impact on the public. Since these wastes are of low specific activity even a severe accident would not release a major amount of radioactivity. Minor releases might cost a few hundred dollars to clean up, but no significant public exposure should occur if normal precautions are taken.

More than 20 years of experience has shown that the prevailing techniques, characterized by multiple means of protection and by large safety margins, do work. The record of US experience during the past 19 years shows that only 119 transportation 'incidents' occurred although hundreds of thousands of shipments were made each year. In 84 of these no radioactive material was released from the package. In none of the 35 cases in which material was released was there any serious resultant exposure to radiation. Only one case resulted in dispersal into the air, and only one case required costly cleanup. Other nations report similar experience.

As the nuclear power industry grows both the numbers of persons professionally exposed to radioactivity and the number of accidents which occur during transportation of radioactive material can be expected to increase. It can be said that:

- No physical, technical or organizational problem prevents the achievement of a safe and manageable transport system.
- The recognition that accidents in transportation will occur should not be equated with public exposure to radiation.

To protect the public and the environment from the possible adverse effects of the transportation of nuclear materials responsible national and international authorities should continue to review and harmonize transport regulations and standards. Additionally, for each proposed nuclear power plant, a technical assessment of potential transportation 'impacts', considering a range of known distances between sites and the probabilities and consequences of serious accidents, should be made. With this information at hand the overall risk from transport accidents can be estimated, and the actions which should be taken to minimize them can be determined.

Public Health and Safety Programmes

Despite the unprecedented precautions which are taken to make nuclear power reactors safe and foolproof one can reasonably anticipate that accidents will happen eventually as a result of errors in design, failures in equipment, mistakes of man, sabotage and acts of God — floods, tornadoes, earthquakes and so on. As the number and variety of power reactors increase a few accidents ranging widely in severity can be expected; it is certain that major accidents will occur far less frequently than minor accidents or incidents. The vast majority of radiation incidents will result from buildup of radioactivity in the primary and/or secondary cooling system, leaking of contaminated fluid through gaskets, stuck fuel elements resulting in building contamination, slight increases in the building background radiation levels, contamination of water in the pool storage area, clothing contamination and so on.

Operational health and safety programmes

The principal objectives of health and safety programmes associated with a nuclear power plant are to assist plant management in reducing the number and severity of accidents, to detect at an early stage significant perturbations in reactor operation which, if not corrected, may lead to reactor accidents, to be alert to increases in levels of radiation background and to take immediate remedial actions which assure appropriate correction before rather than after accidents have time to develop. It is generally accepted that nuclear power reactors in the future can and will be constructed and operated in such a way that increases in radiation background in the environment due to routine reactor operations will be kept essentially to zero. Public health problems and radiation risks associated with such plants therefore relate almost entirely to accident potential, or to the frequency and magnitude of reactor accidents. During non-routine operations — such as freeing a stuck fuel element or cleaning up a high-level surface contamination in a section of the pool storage area — personnel trained in health physics are present throughout in order to ensure that operating personnel are not exposed unduly to radiation.

Those assigned to radiation protection functions in the power station organization advise the plant managers who are responsible, together with public health agencies, for protecting the public living in the neighbourhood of these plants against excessive exposure to radiation. Such personnel, under the direction of the plant senior health physicist, are an integral part of both plant management and the plant work force. The members of this organization are familiar with every detail of the design, construction and operation of the installation and provide the interface between operations of the plant and associated problems of environmental protection; and they also provide the primary contact between the plant and the responsible public health agency. The details of organization vary from plant to plant and country to country but, in each case, close co-operation and a strong link between the health physics staff of the plant and those of the public health agency are essential in providing for the safety and well-being of plant employees and residents in nearby communities.

Radiation risks are not the only concern of those responsible for the prevention of pollution of the environment, and protection of the public. Although problems of 'conventional' safety (such as fires, explosions, odours and so on), chemical wastes, thermal pollution and sanitary sewage of the nuclear power station are of types which are customary in other industrial operations, they, too, must be kept under proper surveillance and in conformity with public health standards. Here, the responsibility for safe plant operation and for liaison with public health authorities usually rests primarily with the plant medical director but, in some cases and because these problems are small, this responsibility is placed in the hands of the senior health physicist.

This man, because of his close contact with operations, plays a key rôle both in protecting the health of employees and of members of the public who may be at risk of exposure to radiation, and in preventing and limiting the consequences of reactor accidents. As an adviser to the plant manager he has a major responsibility for providing effective and reassuring responses to local expressions of public concern, preventing radiation accidents and minimizing harm they might do the public should they occur. Responsibilities for radiation protection begin long before the start-up of the plant, and the central purpose of this programme is to minimize human exposure to ionizing radiation by preventing radiation accidents, rather than in supervising appropriate remedial measures after the event. Nevertheless, one of the essential tasks of the radiation protection organization is to develop and implement an adequate emergency plan which should provide, inter alia, for:

- close co-ordination with health physics officials of local, state and national public health agencies;
- close co-ordination with organizations and authorities in local communities such as the police, fire and health departments, hospitals, doctors, transport officials, communications media and so on;
- frequent up-dating of plant emergency plans and the conduct of occasional emergency drills which involve the whole plant; and
- guidance for action to be taken if a major accident takes place.

Specific plans for action during emergencies would indicate details of what must be done following an accident, including important actions which must be taken immediately. It may seem misplaced effort, to prepare elaborate and detailed plans for a major nuclear power reactor accident involving the release to the environment of a few thousand to several hundred million curies of radioactivity, when it has been estimated that such an accident would not be expected in a given plant more often than once in 10 000 years; but consideration of all safety aspects and plans to handle all eventualities to the extent that they can be visualized are characteristic of the nuclear energy industry. It has one of the best safety records of all modern industries.

The rôle of health authorities

The early applications of ionizing radiation were restricted mostly to medicine, but at an early stage it became obvious that radiation could have harmful effects. Only the immediate somatic effects were then recognised, and these affected a relatively small number of people — doctors, nurses, engineers and patients. As the application of X-rays and natural radioactive substances for various purposes and in biological research spread, the long-term and genetic effects became acknowledged; eventually many countries were compelled to provide legislation, rules and regulations aimed at giving protection against them. The rapid development in the use of nuclear techniques in the many and varied applied sciences increased the potential danger of exposure to radiation in a way which had no precedent. This development took place against a background of nuclear weapon development and testing, and caused the public naturally to mistrust the use of energy of nuclear origin. This mistrust is still apparent, 30 years later.

The public health service of any country has a basic responsibility for ensuring, promoting and creating favourable conditions for preserving and improving the standard of health of the population. But it took some time for many health authorities to realise that the increasing use of ionizing radiation and radioisotopes and the development of atomic energy opened up new responsibilities in the public health context, and that ionizing radiation and radioactive material were new factors in environmental hygiene and a part of environmental pollution — although relatively small and of minor importance for the time being. It is widely acknowledged that the control, surveillance and monitoring of radioactive pollution should, and that the evaluation of results including the drawing of conclusions must, rest with the public health authorities for two reasons. First, the noxious effects of ionizing radiation are cumulative, whatever their source, and exposure resulting from the development of atomic energy should therefore be considered together with radiation exposure from all other uses of ionizing radiation; and secondly, authorities concerned primarily with the promotion of modern techniques rather than health might be accused by the public of exercising biased judgement and of having a vested interest in underplaying the potential hazards of radioactive pollution which might accompany the development of such techniques.

Public health organizations at the local, national and international levels must play a leading rôle in easing the impact of all forms of power production on the health, peace of mind, economy and general well-being of the public. It is obvious that the duties of public health authorities cannot be discharged without very close collaboration with other authorities responsible for matters such as agriculture, energy and transportation. Careful co-ordination between these various authorities is essential to the successful management of the control of radiation exposure. The organization of various government services no doubt varies according to national conditions and traditions, but in general the public health (or environmental protection) agency or agencies are a single focal point for evaluation of the total health impact of all sources of radiation, and can ensure that adequate health protection measures are taken. Public health and/or environmental protection agencies can and do work in the following five principal areas:

- establishment of broad environmental guidelines and standards within which the industry must operate;
- identification and measurement of sources of radiation exposure of the population;
- assessment and evaluation of these exposures with respect to the biological hazards to various population groups (one outcome of this is the stimulation and conduct of research);
- co-operation in the development and application of methods of control, including the provision of a staff suitably trained and equipped to provide advisory and supervisory services in radiation protection;
- co-operation in the conduct of programmes for the training of appropriate technicians and specialists, as well as information and education of both professionals and public as to the total health impact of radiation sources.

If a public health programme is to be effective in easing the impact of nuclear power production on a community the competent agency must have proper authority in its area of responsibility, and appropriate financial support from the government under which it works. It must develop a competence which is recognised and respected by the public whom its programme is designed to protect, and by the nuclear power station organization with which it is concerned. Certainly, it must be backed up by adequate regulations and laws which, if necessary, can be enforced in a court of law. Once a public health programme conducted by well-trained, competent and highly-qualified personnel has been established it must become a centre for the exchange of information on questions of radiation risk raised by members of the community and by the various organizations of which they are a part. In this way questions of concern for radiation dangers that are imagined or feared by the public can be answered before they become the subject of major public controversy.
But before a public health organization can merit the complete confidence of the public and be expected to assume this most important rôle in a community it must demonstrate its competence. It must be able to root its conclusions and recommendations not solely in calculations, inspections of operations and records of the nuclear plant operating authority but in appropriate measurements and observations made under its own auspices. If regulations, codes of practice and laws are not sufficient to protect the public to the necessary extent then the public health organization or agency must be instrumental in making them adequate, and it must see that such laws are so drafted as to be enforceable.

Environmental monitoring programmes are best developed on the basis of close co-operation between the public health organization and the personnel of the nuclear power plant. Adequate monitoring can reassure members of the community that frequent measurements are being made by experts from both the power company and the local public health organization, and that these measurements either continue to confirm the claim that radiation exposures are negligible, or lead to immediate action by the health authority if they are not. However, excessive monitoring programmes can have the reverse effect, of creating alarm by suggesting that widespread measurements are necessary because of potential or suspected releases from the plant.

In addition, the health physicists of the public health organization and of the nuclear power plant must co-operate in working out details of the emergency plan, as discussed previously.

The existence of various international recommendations and standards has had the beneficial effect that there is a fair degree of uniformity in the provisions at the national level as to the maximum permissible doses for radiation workers. Some differences do exist, however, particularly in radiation protection limits specified for members of the public. These are generally the result either of a failure to revise legislation based upon recommendations which have become out-of-date, or of a different philosophy. Legislation on radiation protection can place the burden of implementing different regulations on different authorities. Where multiple national organizations are involved one of them should be designated to serve as coordinator.

The rôle of international organizations

The basic standards for radiation protection have been recommended by the ICRP, which continues to meet periodically to review and up-date these standards. The ICRP standards are recommended by the World Health Organization (WHO), are used as a basis for the standards published by the International Atomic Energy Agency (IAEA) and are accepted in the Convention on Protection of Workers Against Ionizing Radiation prepared by the International Labour Organization (ILO). They are also accepted by regional organizations such as EURATOM and the European Nuclear Energy Agency (ENEA), and have been used as the basis for regulations in a number of States.

Safety standards, codes of practice and guidebooks have been developed by the IAEA, often in cooperation with WHO, to provide guidance on how the basic radiation protection standards can be met. Thirty-six of these manuals have been published in the IAEA Safety Series. Standards, codes of practice and guides have also been issued for specialized applications of radiation — for example, the joint ENEA/IAEA publication **Radiation Protection Standards for Radioluminous Timepieces** and the **IAEA/ENEA Guide for the Safe Design, Construction and Use of Radioisotope Power Generators.**

International organizations can also play an important rôle in the drafting of model regulations for use by Member States. This can do much to assure harmonization of policies and regulations from State to State. For example, the IAEA has issued transport regulations which are mandatory for its own work and which are recommended to its Member States and other organizations as a suitable basis for their own regulations. These have been adopted in the regulations and recommendations of the International Air Transport Association (IATA), the Intergovernmental Maritime Consultative Organization (IMCO) and the Council for Mutual Economic Assistance (CMEA). They also form the basis for the relevant annex of the International Convention for the Transport of Goods by Rail (CIM), applicable in 24 European and neighbouring countries, the Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) and the draft Agreement Concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN), both prepared by the Economic Commission for Europe of the United Nations. The Universal Postal Union (UPU) has adopted regulations which permit the carriage of radioactive material by post within the exemption limits provided by the IAEA regulations. The regulations have also been adopted by a substantial number of individual Member States.

The United Nations Scientific Commitee on the Effects of Atomic Radiation (UNSCEAR) was established on 3 December 1955 to evaluate the radiation doses and risks from global contamination by radionuclides released in the atmospheric testing of nuclear weapons. Assessments for all sources of radiation exposure constitute an appropriate task for such an international body, provided emphasis is places on the global or international implications of such exposures. Other specialized agencies can assist in this effort by accumulating and making available the required information; for example, the IAEA can assemble information on releases of radionuclides to the environment, FAO can assemble information on the levels of radionuclides in foodstuffs and WHO can secure information on radioactive contamination of human tissues. Since the radiation exposures from peaceful uses of atomic energy to date have been both negligible and local care is needed to ensure that international activities do not duplicate national programmes unnecessarily.

A primary activity of international organizations is in the collection and dissemination of information. One of the simplest methods is through the sponsorship of well-conceived international and regional panels, symposia and congresses — especially those which result in the publication of proceedings which form a permanent record and make the information presented available to a much wider audience. In planning such meetings great attention must be paid to the choosing of appropriate and timely subjects for discussion, and each should be focussed on a specific audience. In many cases co-sponsorship with a scientific or professional society has distinct advantages in that it identifies the subject area and the audiences more clearly and, most importantly, it helps members of these organizations realize that these are their problems, and that they must take the initiative and share the responsibility for finding acceptable solutions.

The IAEA and WHO have both been active in collecting and disseminating information on activities relating to public health and environmental aspects of atomic energy programmes. The IAEA has published directories or whole-body radioactivity monitors and of waste management facilities. They also publish annually research abstracts on waste management and on health physics; these abstracts fill a special need, especially for developing countries, in that they describe current research rather than work that is already completed and published. The WHO has established International Reference Centres on Waste Disposal, on Air Pollution and on Environmental Radioactivity. The first undertakes a broad programme including collection and dissemination of information, co-ordination of research, training of personnel and provision of advisory services related to the collection, treatment and disposal of radioactive waste. One of the functions of the centres on air pollution is to collect data systematically and to conduct measurements on air pollutants in urban areas around the world. The third class of centre collects data on the environmental levels of radiation and takes steps to ensure that the data are comparable by standardizing the sampling and measuring techniques used, and arranging for inter-laboratory comparison.

Yet another effective method of information collection and dissemination is in the employment of experts to prepare handbooks and other types of publication on pertinent subjects.

Recently the IAEA established a scheme in co-operation with its Member States using computers to assist in the collection and dissemination of information relating to nuclear science and its peaceful application. In this scheme, the International Nuclear Information System (INIS), co-operating Member States are called upon to prepare descriptions of pertinent scientific literature published in their areas, and to submit this information to the IAEA for dissemination through INIS to others.

The information disseminated need not be highly "scientific", Publications are quite often prepared in an attempt to give the interested layman a simple and concise but technically accurate description and discussion of activities in atomic energy. The IAEA, other specialized agencies and national authorities also have active public information programmes. The IAEA has published, for example, an information circular entitled Nuclear Energy and the Environment which contains a short review of the efforts made by the nuclear industry to protect man and his environment.

One programme carried out by international organizations has been helpful in increasing confidence in radiological protection programmes: that is, support of inter-calibration studies. This work has been very valuable, bringing together health physicists from public health authorities and nuclear power operations to conduct experiments with various sources of radiation and to determine the accuracy of dose measurements of the various systems now in use. The types of instruments and techniques that should be compared and evaluated in such a programme are, for example, whole-body counters, low background environmental measurements, criticality instrumentation, and ecological sampling of the environment of a nuclear power plant. Attention might also be given to the development of reference methods for radiochemical analysis, and inter-laboratory comparison of results.

When Member States have specific problens on which they need expert advice international organizations can provide advisory services and technical assistance. Experts from the staff of the organization, or from other Member States, can be made available to the requesting country for specified periods of time ranging from a few weeks to more than a year, depending on the time needed to complete the task. Assistance can also be given in the form of specialized scientific equipment.

International organizations can also play an important rôle in education and training, in a number of ways. Fellowships are made available to scientists and engineers from developing countries to enable them to work or to study for some time in one of the more highly developed countries. If these assignments are adequately planned the visiting fellow has an opportunity to become familiar with a wide spectrum of activities related to public health and environmental problems associated with atomic energy programmes.

Research contracts are designed to fulfil two objectives: first, to encourage and support research considered necessary to complete the general understanding of the effects of effluents from nuclear installations on public health and the environment, and secondly, to give support — especially to young scientists — for the initiation of research programmes that are expected to expand and flourish with private or government support when the value of the programme is recognized.

Training courses on topics which are of particular interest to a given region are organized. Experts are made available from the staff of the organization(s) involved and from Member States. In addition to lectures the participants are given the chance to do practical work at the facilities of the host country. Training films may be produced for use in such courses, as well as for more general use in Member States.

Study tours in which scientists and engineers from developing countries can visit a number of facilities in more advanced countries are often organized. The study tour usually includes lectures and practical exercises, as well as a detailed technical description of the operation of each facility by local staff members.

International organizations have as well the opportunity to convene small groups of experts as consultants to discuss present and future problems of the most importance to Member States and the world community as a whole. In this way the programmes of the international organization can not only be kept relevant to issues of current concern, but reflect those that are likely to arise in the future.

Finally, the international organizations can send representatives to international meetings. Often problems take on a different character when viewed from an international, as opposed to a national or regional, standpoint. Participation by representatives of international organizations in meetings can help to balance views.

summary

Civilization has developed largely as man has devised new ways of changing and controlling his environment. Since the beginning of the industrial revolution the impact of man on his environment has grown at an ever-increasing pace. The great changes in our environment which have occurred in recent years, and the still greater changes which threaten as the combination of higher living standards and increasing world population demand ever-increasing rates of energy production, have provoked a call for closer control of these changes. It seems no more than common sense to urge that the environment should be harmed as little as possible.

In most places additional power is needed to assist peoples in attaining improved standards of nutrition, housing, clothing, public health and so on. In these situations the decision is not whether additional power should be produced but how it can be best produced, considering both the source of energy and the method used to convert it to electricity.

Several factors enable one to conclude that nuclear power use will increase and that it will play a complementary, as well as a competitive, rôle with fossil fuels in the future production of electricity. Economic considerations suggest that the base-load supply will be provided by nuclear plants, and the peak-load by fossil-fuelled plants.

The undertaking of any large-scale enterprise involves disturbance of the environment. The production of electrical energy is no exception, but many of the disturbances are not due to the nature of the fuel but are associated with normal processes of plant construction and with ancillary operations. The environmental disturbances associated with the construction of a nuclear power plant are often less than those of coal-fired plants, since considerably smaller sites are required. Both fossil-fuel and nuclear plants release thermal energy, as waste heat, and small amounts of radioactivity to the environment, but with respect to atmospheric pollutants nuclear plants are decisively better than fossil-fuelled plants.

All steam-electric generating plants have a common potential problem with the need to release heated water to the environment. Heat from combustion of fossil fuel or from the fission of nuclear fuel in a reactor produces steam at high temperatures and pressure which in turn drives a turbine connected to a generator. The "spent" steam from the turbine is condensed by passing large amounts of cooling water through condensers. Modern steam turbines operating with fossil fuels attain thermal efficiencies of 37-38%. Most present-day nuclear power plants are thermally less efficient than these modern fossil-fuelled power plants, although they are comparable in efficiency to the average of all fossil-fuelled power plants now in operation. In fossil-fuelled power plants part of the excess heat is released to the atmosphere in the flue gases, whereas in nuclear power plants essentially all of the excess heat is transferred to the cooling water. As a result, a nuclear power plant in which once-through cooling is used will discharge about 50% more waste heat to the receiving waters than a fossil-fuelled power plant producing an equal amount of electricity. Gas-cooled and liquid-metal-cooled advanced reactors of the future are expected to attain higher thermal efficiencies, equal to or exceeding those of conventional plants. However the problem facing the electrical power industry is not only how to produce more efficient power stations and limit thermal pollution at the source, but also how best to manage the thermal releases that occur. Local circumstances, rather than global considerations, will dictate the most appropriate methods of management.

The use of atomic energy as compared with fossil fuel for the production of electricity will affect the environment in a number of ways:

- drastically reducing the mining and transport of fuel;
- increasing by some 50 per cent the heat released into cooling waters from power plants which are built initially, though in respect of later plants the increase will be negligible;
- introducing a very small risk of local release of lethal amounts of radioactive substances, by accident;
- requiring small restricted areas for disposal of fission products and for decommissioned reactors;
- slightly increasing the world inventory of krypton, and later tritium, but decreasing the inventory of radon in the atmosphere;
- virtually eliminating the emission of particulates, sulphur dioxide, carbon dioxide and mercury to the atmosphere;
- eliminating problems in the disposal of fly ash.

The basic standards for radiation protection have been recommended by the International Commission on Radiological Protection. These recommendations have been accepted by the World Health Organization and the International Labour Organization, and are used as the basis for standards prepared by the IAEA. They have also been translated into regulations, codes of practice and working standards by individual countries and by international and regional organizations. These standards have evolved from numerous studies in many countries of somatic effects and hereditary effects at high radiation exposures. Maximum permissible values have been established at radiation exposure levels which are considerably lower, at which somatic damage has not been observed and hereditary effects are believed to be at a very low incidence. Effects at these low levels have been computed by assuming that the ratio of effect to exposure is the same as at the much higher exposures at which effects were observed (the linear dose-effect hypothesis). This calculation is believed to be safe and conservative, although the actual relationships cannot be proved on the basis of direct observation. For this reason the ICRP recommends that radiation doses should be kept as low as is practicable.

A number of reactor types are being developed and marketed currently. Each presents special requirements with regard to handling and control of the radionuclides generated, but for each type appropriate systems of control have been developed. This attention to the need to ensure public safety and to prevent damage to the environment has led to the excellent record of minimal radiation exposure of the public discussed above.

Provisions are made in the design and siting of power reactors and of ancillary nuclear facilities to cope with potential accidental releases of radioactivity as well as with routine releases.

The technology required both to prevent accidents and to mitigate their possible consequences should they occur is fundamental to the designing of nuclear installations in such a way as to afford maximum protection to the environment. The safety record of the nuclear industry has been particularly noteworthy: the few accidents that have occurred have been well within the capability of the installations concerned to contain the abnormality and to protect the public.

However it should be recognized that major reactor accidents, although very unlikely, may occur. There is a popular tendency to accept familiar hazards while reacting violently to unfamiliar ones. Since radiation hazards are not familiar and may be cumulative and irreversible as well as entailing possible genetic risks, it is prudent to undertake public health measures to educate the public and to assure it that proper care is taken to protect it by

- building a safe reactor;
- caring for its good siting;
- ensuring its safe operation;
- being prepared to minimize the effects of possible accidents;
- undertaking a programme to improve power reactors and facilities and their operations continually to reduce further the probability of accidents and to profit from experience with minor accidents.

The most serious radiological health problem associated with atomic energy has been the overexposure of uranium miners. During the past 20 years some 100 uranium miners have died of lung cancer in the US, and it has been estimated that 500-1500 more of those over-exposed prior to the establishment of the present occupational safety standards may also die of this radiation related disease. The incidence of lung cancer was much greater among miners who were cigarette smokers, but the exposure to daughter products of ^{222}Rn was the primary factor implicated. The present levels for working conditions have been established at much lower working levels than that to which these miners were exposed, perhaps by as much as a factor of several thousand, and future risks of lung cancer of uranium miners should be greatly reduced.

In the atmospheric testing of nuclear weapons a large fraction of the radionuclides created were injected into the stratosphere (the upper part of the atmosphere), where they reside for long enough times (several months to several years) to become globally dispersed before deposition on to the surface of the earth. In the nuclear power industry most of the radionuclides are contained rather than released. Atmospheric releases that do occur are to the troposphere (the lower atmosphere), where the residence times are of the order of a few days to a few weeks. Thus most releases give a rise to contamination problems of a local nature. However, a few radionuclides have sufficiently long half-lives and environmental mobility to become globally dispersed. These include tritium, ^{85}Kr, ^{129}I and ^{14}C. Iodine-131, with a half-life of about 8 days, is not normally

A smoggy morning in downtown Chicago.
Smoke, generated by industry,
is being held close to the surface by a temperature inversion.
Photo: Argonne National Laboratory

of global concern, but is of special concern in accident situations. These radionuclides are of special interest internationally because their release may affect populations outside the immediate area of their release. Because of the very rapid growth projected for the nuclear industry it is advisable to continue to review information on the releases and concentrations of these radionuclides in various sectors of the environment. If there arises a need to control these emissions it is more easily done at the source.

Well over 99.9% of all the radioactivity generated in nuclear power reactors is contained within the fuel elements until they are reprocessed for recovery of unburned fuel. Thus careful control of the inventories in reactor, and of the spent fuel which must be handled and transported to fuel reprocessing plants, is required.

The IAEA has issued transport regulations which are mandatory for its own work and which are recommended to Member States and international organizations as a suitable basis for their regulations. Reliance is placed on safety features built into the packaging and the requirements are especially stringent for packaging of highly active materials to prevent loss of containment in the event of an accident. To date no country has experienced a release of activity from a package of high-level activity.

A reprocessing plant may accommodate the spent fuel from several reactors, and it is during the reprocessing of the fuel that high-activity wastes are generated. These wastes must be kept in containment for very long periods of time, ranging from a few centuries to possibly thousands of years, if they contain substantial quantities of transuranic elements. Although storage as liquids in specially constructed tanks near the ground surface has been a suitable and reliable method for containment of these wastes to date, processes of solidification have been developed and some countries have already decided that such wastes will be solidified to reduce the potential "environmental mobility" of these wastes during long periods of time. Consideration is also being given to various means of storage of these wastes, including their storage in deep, dry and stable geologic formations in order to assure further their isolation from the human environment for the time required.

Attention must be given to problems of radiological health at all levels ranging from plant operations, to local and national public health authorities and to international organizations. Plant personnel must institute procedures which ensure that normal releases of radionuclides are within the limits prescribed by local and national authorities and which reduce the number and severity of accidents. In the unlikely event that an accident occurs they must have developed, in co-operation with local and national public health authorities, procedures which will reduce the radiological impact upon local populations.

Public health authorities have a basic responsibility for protecting public health and should develop the standards within which the industry should operate.

International organizations provide forums for discussion which allow States to discuss common problems. Although they have no direct regulatory rôle they can promote the harmonization of principles on which national regulations are based, thus helping to ensure that the degree of protection of public health is uniform from State to State. The international organizations also play an important rôle in the collection and dissemination of information on key issues.

Man has been exposed continually to natural ionizing radiation resulting from cosmic rays and from the decay of radioactive substances on earth. Dose rates from these sources are highly variable, depending on elevation above sea level, local geology, seasons, dietary habits, types of residential construction and so on. However, UNSCEAR has estimated that the average annual gonadal dose received by the world population from natural sources amounts to about 100 mrads.

The world-wide population dose from man-made radiation sources is still less than levels incurred from natural sources, but the background level is being approached in at least one industrialized nation. The average **per capita** whole-body dose in the United States is estimated for 1971 to be 114 mrems, compared to the average dose of 130 mrems per year from nature. Most of the man-made exposure (more than 90%) is received as a result of medical procedures for diagnosis and treatment of disease. Operation of nuclear power stations, fuel reprocessing plants and other atomic energy facilities resulted in minute exposures to the total population, about 0.013 mrems per year. Thus, even with a projected increase in nuclear power production by a factor of a hundred it is not likely that it would contribute significantly to the total radiation exposure.

This should not imply that the control of radionuclides in the nuclear power industry should be relaxed. In keeping with the basic recommendation of the ICRP, the management of radioactive wastes is concerned with keeping the total addition of radiation exposure of man as low as practicable. Whenever practicable, radioactive materials are concentrated and contained in isolation from man's environment until their radioactivity has decayed to innocuous levels.

When release to the environment is necessary the rates of release are kept low enough not to exceed the local capacity of the environment to disperse and dilute the materials to acceptably low concentrations. In this respect the environmental processes that may lead to reconcentration and may provide a pathway for man's exposure to additional radiation must be considered. Radioactive effluents released from nuclear power plants and other facilities are always monitored as a means of control and public protection. Additional off-site monitoring is carried out as a confirmatory means of environmental protection, but in general releases have been so low that little indication can be found of radiation above natural background levels.

It may be true that cutting the rate of increase of power expansion may reduce detrimental environmental effects. But this is unlikely to occur, and in most cases is probably undesirable. A better solution would be to improve power production in such a way as to reduce detrimental effects on the environment to an acceptable level. To that end, and to ensure that total doses of radiation in man-rems are limited:

- the nuclear power industry must continue to operate safely. Internationally agreed guidelines and codes of practice are desirable for the siting, design, construction and operation of nuclear power plants and associated facilities. These should refer to preventive measures to exclude or minimize accidents as well as to plans and equipment necessary to mitigate the effects of accidents and to protect the public.
- New and improved methods of management of radioactive wastes from nuclear facilities with special emphasis on environmentally mobile, long-lived radionuclides such as tritium, ^{85}Kr and ^{129}I need to be developed;
- there is also a need to assess the impact upon man of releases of radioactive materials from the nuclear industry;
- and research concerning the environmental behaviour of long-lived critical radionuclides should be continued.

The projected growth of nuclear power and the potential public health risks involved, however small, require that diligent controls should continue to be practised. The public is quite aware of the risks involved, and it is necessary and proper that the nuclear industry exercise careful control to minimize these risks — while maximizing benefits to the public — and keep the public informed about them. The timely public acceptance of nuclear power may be as important as is the development of the technology itself.

Annex I.
Pertinent Publications of the International Atomic Energy Agency

Safety Series

No.	Title	Date of issue	Remarks
4	Safe operation of critical assemblies and research reactors (Revised, see S.S. No.35)	1961	Guide-book
5	Radioactive waste disposal into the sea	1961	Guide-book
* 6	Regulations for the safe transport of radioactive materials	1961	Safety Standard
	Revised	1964	
	"	1967	
	"	1970	
	w/List of National Competent Authorities w/Advisory material on packaging for large radioactive sources (April 1967)		
7	Regulations for the safe transport of radioactive materials — Notes on certain aspects of the regulations	1961	Guide-book
8	The use of film-badges for personnel monitoring	1962	Guide-book
* 9	Basic safety standards for radiation protection	1962	Safety Standard
	Revised	1967	
10	Disposal of radioactive wastes into fresh water (For Revised Edition 1970 see S.S. No.36)	1963	Guide-book
11	Methods of surveying and monitoring marine radioactivity	1965	Guide-book
* 12	The management of radioactive wastes produced by radio-isotope users	1965	Safety Standard
* 13	The provision of radiological protection services	1965	Safety Standard
* 14	The basic requirements for personnel monitoring	1965	Safety Standard
15	Radioactive waste disposal into the ground	1965	Guide-book
16	Manual on environmental monitoring in normal operations	1966	Guide-book
17	Techniques for controlling air pollution from the operation of nuclear facilities	1966	Guide-book
18	Environmental monitoring in emergency situations	1966	Guide-book
21	Risk evaluation for protection of the public in radiation accidents	1967	Guide-book (Joint IAEA/WHO publication)
24	Basic factors for the treatment and disposal of radioactive wastes	1967	Guide-book
* 26	Radiation protection in the mining and milling of radioactive ores	1968	Code of Practice (Joint IAEA/ILO publication)
27	Safety considerations in the use of ports and approaches by nuclear merchant ships	1968	Guide-book

No.	Title	Date of issue	Remarks
28	Management of radioactive wastes at nuclear power plants	1968	Guide-book
29	Application of meteorology to safety at nuclear plants	1968	Guide-book
* 31	Safe operation of nuclear power plants	1969	Code of Practice
32	Planning for the handling of radiation accidents	1969	Guide-book (Joint IAEA/ILO/FAO/ WHO publication)
34	Guidelines for the layout and contents of safety reports for stationary nuclear power plants	1970	Guide-book (Joint IAEA/WHO publication)
* 35	Safe operation of research reactors and critical assemblies w/Technical Appendix	1971	Code of Practice (Joint IAEA/WHO publication)
36	Disposal of radioactive wastes into rivers lakes and estuaries (Revised Edition of S.S. No.10)	1971	Guide-book

* Safety Standards and Codes of Practice are submitted to the Board of Governors for approval before publication.

Technical Reports Series

No.	Title	Date of issue
15	A basic toxicity classification of radionuclides	1963
27	Technology of radioactive waste management avoiding environmental disposal	1964
31	Training in radiological protection: curricula and programming	1964
78	Operation and control of ion-exchange processes for treatment of radioactive wastes	1967
82	Treatment of low- and intermediate-level radioactive waste concentrates	1968
83	Economics in managing radioactive wastes	1968
87	Design and operation of evaporators for radioactive wastes	1968
88	Aseismic design and testing of nuclear facilities	1968
89	Chemical treatment of radioactive wastes	1968
101	Standardization of radioactive waste categories	1970
106	The volume reduction of low-activity solid wastes	1970
109	Personnel dosimetry systems for external radiation exposures	1970
116	Bituminization of Radioactive Wastes	1970
118	Reference methods for marine radioactivity studies	1970
120	Monitoring of radioactive contamination on surfaces	1970
122	Air filters for use at nuclear facilities	1970
133	Handbook on calibration of radiation protection monitoring instruments	1971

Proceedings Series

Symbol.	Title	Date of issue
STI/PUB/18	Disposal of radioactive wastes	1960
STI/PUB/57	Reactor safety and hazards evaluation techniques	1962
STI/PUB/60	Biological effects of ionizing radiation at the molecular level	1962
STI/PUB/63	Treatment and storage of high-level radioactive wastes	1963
STI/PUB/72	Siting of reactors and nuclear research centres	1963
STI/PUB/78	Radiological health and safety in mining and milling of nuclear materials	1964
STI/PUB/84	Assessment of radioactivity in man	1964
STI/PUB/116	Practices in the treatment of low- and intermediate-level radioactive wastes	1966
STI/PUB/126	Disposal of radioactive wastes into seas, oceans and surface waters	1966
STI/PUB/154	Containment and siting of nuclear power plants	1967
STI/PUB/156	Disposal of radioactive wastes into the ground	1967
STI/PUB/159	Assessment of airborne radioactivity	1967
STI/PUB/195	Treatment of airborne radioactive wastes	1968
STI/PUB/199	Radiation protection monitoring	1969
STI/PUB/226	Environmental contamination by radioactive materials	1969
STI/PUB/239	Nuclear energy costs and economic development	1970
STI/PUB/261	Environmental aspects of nuclear power stations	1971
STI/PUB/264	Management of low- and intermediate-level radioactive wastes	1970
STI/PUB/285	Tests on transport packaging for radioactive materials	1971
STI/PUB/289	Rapid methods for measuring radioactivity in the environment	1971

Other Publications

Title		Date of issue
Waste Management Directory		1971
Waste Management Research Abstracts, No.	1	1965
	2	1966
	3	1967
	4	1968
	5	1970
	6	1971
Health Physics Research Abstracts, No.	1	1968
	2	1969
	3	1970
	4	1972

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Annex III.
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List of Consultants and Contributors

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List of Consultants and Contributors

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