DECEMBER 1978 NUMBER 266

ATOM

REACTOR ACCIDENTS AND THE ENVIRONMENT

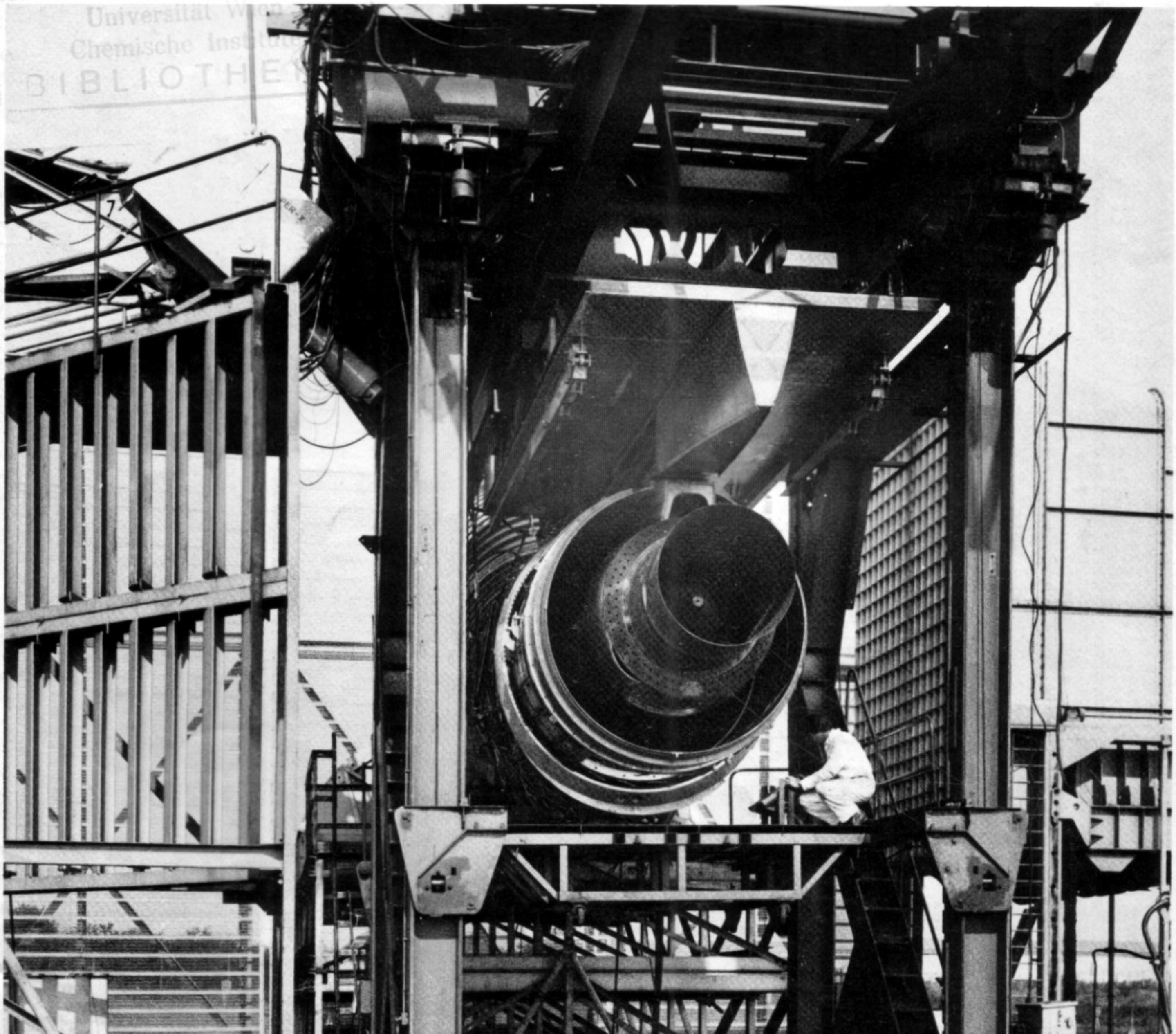
THE ECONOMICS OF NUCLEAR POWER

THE NONDESTRUCTIVE TESTING CENTRE

FUEL—THE BROADER PERSPECTIVE

CRITICAL COMMENT ON THE MANCUSO STUDY

INDEX FOR 1978



DECEMBER 1978 NUMBER 266

ATOM

contents

THE MONTHLY INFORMATION BULLETIN OF THE UNITED KINGDOM ATOMIC ENERGY AUTHORITY

Enquiries concerning the content and circulation of the bulletin should be addressed to the Editor,
James Daglish
Information Services Branch UKAEA
11 Charles II Street
London SW1Y 4QP
Telephone 01-930 5454

Information on advertising in ATOM can be obtained from D.A. Goodall Ltd., Empire House
St. Martins-le-Grand London EC1A 4DR
Telephone 01-606 0577/8/9

Front cover: An RB-211 engine on a test bed at a Rolls-Royce factory undergoing dynamic radiography, work which led to the grant of a Queen's Award for Technological Achievement in April 1978 to the Nondestructive Testing Centre at Harwell, together with the Advanced Projects Department, Test Operations, of Rolls-Royce Ltd. In this issue, a review of the work of the NDT Centre.

REACTOR ACCIDENTS AND THE ENVIRONMENT

This article, by R.F. Griffiths, is a condensed version of a paper by J.R. Beattie, Griffiths, G.D. Kaiser and G.H. Kinchin* entitled *The Environmental Impact of Radioactive Releases from Accidents in Nuclear Power Reactors*, an invited contribution presented to the Nuclear Energy Panel of the International Atomic Energy Agency/United Nations Environmental Programme.

The use of nuclear power for the generation of electricity is now well established in the UK, with about 10 GW(e) capacity in thermal neutron reactors either installed or under construction, and development work on the fast neutron reactor continuing to be the largest single item of expenditure in the UKAEA budget. None of the power reactors in the UK has ever suffered an accident leading to any significant impact on the environment, but the coexistence of a powerful energy source (up to 3 GW thermal power) and a large inventory of radioactive materials (10^9 to 10^{10} curies) in the reactor core means that the potential for such accidents does exist, even though the probability of occurrence is very small. The recognition of this potential has provided the impetus for extensive scientific studies over the years. These investigations point to releases to the atmosphere as being of dominant importance in determining the possible impact of such accidents, and it is to this aspect that we will devote our consideration in this paper.

The measures required for the protection of people against the hazards of ionising radiation are formalised in the publications of the International Commission on Radiological Protection (ICRP). The recommendations of ICRP are regularly reviewed and revised where appropriate. The most recent example of the Commission's work is ICRP 26[1] representing the most up-to-date information and the best sources of knowledge in the field of radiological protection. In this paper a brief survey is given of the nature of the health hazards posed by exposure to radiation in the context of the potential impact of accidental releases from power reactors.

The dispersion behaviour of materials released to the atmosphere is of itself a vast field of study, with many areas of application. Methods developed at SRD for use in the assessment of potential hazards from reactor accidents are described here.

The input to a set of calculations of dispersion in the atmosphere must include a description of the inventory and mode of release of the radionuclides involved. The character of the release depends on the type of reactor involved, and consideration is given here to the mechanisms whereby materials may be accidentally released from four principal reactor types that are of particular relevance in the UK, either by virtue of their established use in the UK nuclear power programme (Magnox and Advanced Gas-cooled Reactors) or else by virtue of the possibility of their future adoption as commercial power reactor systems in the UK (Pressurised Water Reactors and Liquid Metal Fast Breeder Reactors).

The idea of probability of occurrence leads naturally to discussion of the concept of risk, which may be defined as the product of the magnitude of a particular consequence and the probability of occurrence per unit time. In the case of death as the consequence suffered, two aspects of risk emerge as being of special interest, namely *individual risk of death,* expressed as the number of deaths per year from a particular cause divided by the total population, and *community risk of death,* which expresses the frequency of occurrence of accidents involving multiple fatalities. Community risk may be expressed in a cumulative form as the frequency of occurrence of an accident in which N or more people are killed, or non-cumulatively as the frequency of occurrence of an accident in which the number killed falls in the range N_1 to N_2. The two forms express the same information in different ways, but conversion from one to the other is a straightforward procedure. From consideration of the measurability of risk one progresses to the wider question of the acceptability of risk. Clearly it is not the scientist's role to dictate what level of risk ought to be accepted, but he can fulfil the important task of collecting and examining evidence on risks that people do accept in practice and, by comparing these with estimates of *potential* risks, deduce what may be generally acceptable to most rational people.

In this paper the environmental impact is considered in terms of injuries and deaths caused to man, and the land areas that might be rendered temporarily unusable. This amounts to asserting that if man at the top of the ecological tree is safe from the radiological impact of accidental releases from nuclear reactors, then so are the flora and fauna that compose that tree. This proposition is often implied, but seldom stated clearly, and it may be that it requires further examination and detailed proof. The conclusion drawn here is that within the stated framework of description, the potential risks of accidents to nuclear power reactors can be judged to be small.

Effects of ionising radiation on man

Exposure to ionising radiation is an inescapable consequence of life on this planet. Natural sources in the environment give an annual dose of about 100 millirem, arising from cosmic rays (about 50 mrem/yr), radioactive materials in the earth's crust (about 30 mrem/yr) and radioactive constituents of the human body (about 20 mrem/yr). Details of the natural background exposure can be found in a report by Webb[2]. This background varies with geographical location, and one might therefore expect to be able to observe some correlation with geographical variations in the incidences of certain diseases, especially cancer, but no such effect has ever been demonstrated. Man-made sources of exposure include the fall-out from nuclear explosion tests,[3,4,5] the use of X-rays for diagnostic and therapeutic purposes, luminous watch dials, television sets, and the very small exposure due to routine discharges to the environment from nuclear installations. All of these man-made sources put together are still considerably less than the natural background exposure.

In the event of an accidental release of radioactive material from a reactor, members of the surrounding popu-

*The authors are members, and G.H. Kinchin is Director, of the UKAEA Safety and Reliability Directorate (SRD), Culcheth.

lation may be exposed in a variety of ways. These include direct external radiation from the plume as it travels downwind, internal exposure due to inhalation of the passing cloud or of material resuspended from that deposited on the ground, and ingestion of contaminated foodstuffs or water. Translocation within the body of inhaled or ingested materials would lead to selective irradiation of various organs of the body depending on the solubility of the substances involved. These exposures could lead to a variety of "early" and "delayed" somatic effects, as well as hereditary or genetic effects among the descendants of the exposed individuals. Quantitative discussion of such effects can be found in appendix 6 of the USNRC Reactor Safety Study by Rasmussen and his associates[6] and in Smith and Stather[7]. A more extensive treatment than is appropriate here will be found in Reference 8; in this paper it will suffice to touch on a few representative aspects. The early effects of radiation are dose dependent; in the human there appears to exist a dose, equivalent to about 100 rads for whole body radiation, below which clinical effects are unlikely. Above this dose pathological changes are due mainly to damage to cell membranes allowing leakage of fluids and electrolytes, and mainly also to loss of reproductive capacity of stem cells leading to a diminution in numbers of mature cells (an early effect in vital tissues such as bone marrow and gut because in these there is normally a rapid turnover of cells).

The major late (or 'delayed') somatic effect of radiation on man is cancer. The risks of radiation-induced cancer have been summarised in various reviews.[6,7,9,10,11,12,13] Data available on cancer incidence usually relate to small groups of people exposed to high doses of radiation at high dose rates, and it is, therefore, necessary in most cases to extrapolate the data to obtain the assessment of cancer risk we require. In this paper, as is usual, a linear no-threshold model is used, i.e., the probability of cancer death is considered to be directly proportional to the total dose. It should be noted that linear extrapolation from effects at high doses and dose rates may in some cases overestimate possible risks. Using this model, the absolute cancer risk is obtained expressed as the number of excess cancers expected to develop (e.g., cancers per 10^6 man-rads). Only human data have been used for calculating these risk coefficients for the late (delayed) effects of radiation. Estimates of risk coefficients have been made for radiation-induced deaths from leukaemia and cancers of the lung, bone, liver, gastro-intestinal tract, breast and all other tissues taken together; these values are shown in Table 1. An estimate is also available of the risk of benign thyroid nodules and this is shown in Table 2. The risk coefficients, which are derived mainly from Reference 7 and which are not dissimilar to those in Reference 6 have been rounded so as not to imply greater accuracy than the data justify. It is also assumed that there is a period after irradiation during which there is a negligible increase in cancer incidence, and that this is followed by a period of increased but constant cancer incidence that lasts for a number of years. For leukaemia the period of incidence is assumed to be from 5 to 20 years after irradiation, and for other cancers the incidence period is taken as from 10 to 40 years after irradiation. It is recognised, of course, that this must be an oversimplification of the real situation.

Table 1. Number of deaths expected from leukaemia and other cancers

Effect	Cancer deaths per 10^6 man rads (low LET)
Leukaemia	20
Lung Cancer	20
Bone Cancer	10
Liver Cancer	10
Gastrointestinal tract cancer	20
Breast cancer	20
Thyroid cancer	5
All other cancers	20
TOTAL	125

Table 2. Risk estimates for incidence of benign nodules and thyroid cancer

	Nodules of cancers per 10^6 man rads (low LET)	
	External Radiation*	I-131 and longer-lived isotopes**
Benign nodules***	100	10
Thyroid cancer	100	10
Deaths from thyroid cancer	5	0·5

*These values apply to doses up to 1500 rads (low LET); for 1500 to 5000 rads take half the values; for > 5000 rads assume no risk. For internal emitters these dose ranges should be increased by a factor of 10.

**Isotopes with half-lives shorter than I-131 are assumed to be equivalent to external radiation.

***For children, double this value

Regarding hereditary effects of irradiation the reader is referred to Reference 7 for detailed information. As stated there, damage to the germinal cells (i.e. gonads) can result in spontaneous abortion or hereditary disease. However, the risk of abortion is difficult to quantify because many occur so early in pregnancy as to be undetectable and, for that reason, abortions are not considered in Reference 7. On hereditary disease, these authors conclude that "in a standard population exposed to radioactivity following a reactor accident, a total of 57 cases of serious hereditary disease per 10^6 man rads (low LET) is predicted over many generations, of which 15 and 9 cases will appear in the first and second generations respectively".

The dose of external gamma radiation from fission products deposited on the ground (and to a lesser extent the beta radiation) which would be received by persons if they remained in the area must be considered, and evacuation of the local population from the area may be required for a time. If a release of volatile fission products had occurred from a thermal reactor, deposited isotopes of iodine and tellurium, which are abundant and have short half-lives, would deliver a significant gamma dose in the first 2-3 weeks; if evacuation of the local population had been required they could then return home. If ruthenium were also released in quantity, a significant gamma dose would be delivered over a period of 1-2 years, determined mainly by the 1-year radioactive half-life of ruthenium 106, although this period might be reduced considerably if the ruthenium were washed away by rain, which on available evidence appears quite likely[14]. Caesium 137 is less abundant but is readily released and has a radioactive half-life of 30 years. Through the gamma emission of its shortlived daughter barium 137m, deposited caesium could deliver persistent levels of whole body radiation exposure. In many soils a large part of deposited caesium 137 is firmly trapped in soil minerals after a period of about a year[14]. Measurements of gamma radiation were made over a period of years above various soils contaminated with caesium 137 and the results are shown in Figure 1 which is based on Reference 15.

Significant skin contamination would probably be picked up from a contaminated environment by children playing outdoors and by men working in the open air, but in less contaminated areas (from which evacuation would be unlikely to be required) reasonable care and regular washing

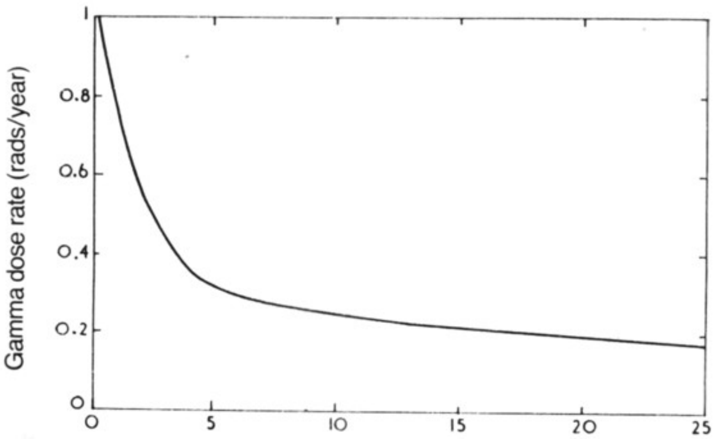


Fig.1 Temporal variation of gamma dose-rate from Cs-137 deposition

could be expected to provide adequate control of this type of hazard. However, there are other ways in which radioactive material originally deposited on ground and vegetation can cause hazard. For example, activity could be ingested accidentally from contaminated hands, particularly in the case of young children; food contaminated by radioactivity in houses and shops could be consumed, and there would be radioactivity deposited on green vegetables in gardens and on other growing crops. All such routes of entry into the human body can be covered by a general statement about ingestion from a contaminated environment, based on studies made at AERE Harwell of uptake of fallout from distant weapons tests; the simple concept emerges that, irrespective of age, one will accidentally ingest the activity from an area of ground of about 10^{-3} m^2/day.

One route, probably the most important, for ingestion of deposited activity is excluded from consideration above, and must now be considered. This is ingestion by humans of iodine 131 in the milk produced by cows grazing contaminated pastures. ERLs of iodine 131, caesium 137 and strontium 90 are given in Table 4 but only that of iodine 131 need concern us in the context of reactor accident releases, since if milk consumption is banned because of iodine 131, the other isotopes mentioned will be automatically taken into account[16].

Maximum permissible levels and Emergency Reference Levels of radiation and radioactivity

In 1965 the ICRP recommended that the cautious assumption should be made that any exposure to radiation may carry some risk[17]. In July 1977 a new version of ICRP recommendations was published as ICRP Publication 26[1] embodying a system of dose limitation, one main feature of which, carried over from the previous recommendations, was that all exposures should be kept as low as is reasonably achievable, economic and social factors being taken into account. ICRP Publication 26 distinguishes between stochastic effects (those for which the probability of an effect occurring, rather than its severity, is regarded as a function of dose, without threshold) and non-stochastic effects (for which the severity of the effect varies with the dose, and for which a threshold may therefore occur). Some somatic effects are stochastic, and of these carcinogenesis is considered to be the chief somatic risk of irradiation at low doses and therefore the main problem in radiation protection. The recommended dose limits for individual members of the general public, based on Reference 17, are listed in Table 3. These dose limits are intended to minimise the risk of somatic effects of radiation occurring among individual members of the general public, and in order to conform to the ICRP's enjoinment, the operators of nuclear installations, and the supervising and licensing agencies, take pains to ensure that any dose received by members of the public is as low as may reasonably be achieved in ordinary circumstances, the limits being approached, if at all, only for short transitory periods.

Table 3. ICRP recommended dose limits for individual members of the general public.

Whole body, gonads, red bone marrow	0·5 rem/yr
Skin, bone, thyroid (but thyroid for children up to 16 yrs. of age 1·5 rems/yr.)	3·0 rem/yr
Other single organs	1·5 rems/yr

The UK Medical Research Council has from time to time published recommendations concerning levels of radiation and radioactivity in the environment and population in the aftermath of a future accident to a reactor or other nuclear facility. The term "Emergency Reference Level" (ERL) has been coined in an attempt to describe more accurately the purpose of recommended levels of this type. According to Reference 18 an Emergency Reference Level (ERL) of dose is briefly defined as the radiation dose below which countermeasures are unlikely to be justified. There are also derived ERLs either of exposure or of activity in environmental materials, which correspond to the ERLs of dose. The ERLs are put forward not as firm action levels but as dose levels at which the responsible authorities should judge whether countermeasures should be introduced, full account being taken of any disadvantages and risks from these countermeasures. ERLs are given in Table 4 for iodine 131, caesium 137, ruthenium 106 and strontium 90. (The ERL of external dose from gamma radiation would be 10 rads average in body tissues, approximately 15 roentgen measured in free air). The ERL carries with it only a very low risk that a person might be hurt by the dose — of the order of 1 chance in 1000 that he will die in the next 40 years. Nevertheless, it should not be thought of as a maximum permissible dose for consideration before an accident has happened, but rather as a guide for action in the aftermath of the accident. The maximum permissible doses must remain those displayed in Table 3.

Atmospheric dispersion and consequence modelling

The fate of material released to the atmosphere from a nuclear reactor will be principally determined by the dispersion processes within the turbulent atmospheric boundary layer. This behaviour is dependent on many interacting phenomena, among which may be numbered the change in the wind speed and direction as a function of height, the rate of incoming solar radiation, the amount of cloud cover, whether the ground is wet or dry, the nature of the surface (whether grassland, forest or city), the topography (whether flat or hilly) and the source of the effluent itself which may, for example, be large enough or hot enough to have a significant influence on the dispersion process. A rigorous treatment of these effects inevitably leads to models of great complexity, the solution of which would be very time consuming even on the most powerful computers. Although such facilities are available, their use in this case would be difficult to justify in view of the existing uncertainties in the input parameters. It is therefore necessary and desirable to simplify the dispersion model used to reduce it to manageable size. The method most widely used employs the conventional Gaussian model of concentration profiles,[19,20] characterised by the *standard deviations* of the concentration distributions in the crosswind and vertical directions. These are monotonically increasing functions of travel distance or travel time. They also depend on the weather category, which is defined by reference to several variables such as the windspeed measured at a height of 10 m, the rate at which the sun is heating the earth's surface, the atmospheric temperature gradient and the amount of cloud cover. At one extreme of the range of weather categories there is a hot, sunny summer's day when the atmosphere is well mixed by convectively generated turbulence and any effluent released into it disperses rapidly. At the other extreme there is a still, cold winter's night with a temperature inversion from the ground upward, when effluent disperses very slowly. Between these categories is a cloudy day with a moderate to brisk wind, which is typical of conditions in which dispersion occurs at an 'average' rate. In the widely used Pasquill-Gifford scheme the weather is conventionally divided into six categories (A to F) ranging from conditions of rapid to slow dispersion[20], and the dispersing plume becomes progressively broader and more dilute as the weather category ranges from Class F to Class A.

As noted in Reference 8, and discussed in detail elsewhere (References 19 to 28 inclusive), allowance can be made for a variety of phenomena that give rise to significant modifications of the behaviour incorporated in the basic Gaussian model. These include mechanisms of depletion of the plume material (for example by radioactive decay, precipitation scavenging, gravitational settling and surface deposition), effects of building wakes and hills, meandering of the wind direction over the duration of the release and the mitigating effects of plume rise fed by sensible heat, latent heat and/or decay heat as well as by the momentum of the released material. Discussion of the limitations of the Gaussian model will be found in References 8 and 29; provided that the user appreciates these limitations, the answers given by the model are probably within a factor of two or three of the reality that the model simulates[22]. Given the uncertainties in the estimation of the other parameters characterising an accidental release, this degree of accuracy is acceptable for purposes of risk assessment.

In order to provide SRD with a flexible tool with which nuclear safety studies can be conducted the Gaussian model with various modifications has been incorporated into a computer code named TIRION[29] which has been used to produce some of the results presented here. Of course, the calculation of concentration profiles is only one step in the process of estimating the consequences of an accident. The doses received by members of the population, the numbers of people affected, and the size of the areas of land contaminated are examples of the output provided by TIRION. This program has been used widely by numerous organisations; its application is exemplified by its recent use in connection with the Windscale Inquiry, by BNFL and by the anti-nuclear Political Ecology Research Group. Codes similar to TIRION have been developed by other bodies, e.g. the CEGB program WEERIE[30].

Using a scheme of calculation such as is embodied in TIRION one may calculate the concentration profile downwind of a given release of radioactive material if the weather conditions are known. If, in addition, the population distribution around the release point is known, and the wind direction is also fixed, one may estimate, for example, the number of people likely to contract cancer, the number who may suffer early death, or how many genetic defects may be transmitted to succeeding generations. In practice one cannot predict what the weather conditions and wind direction will be at the time of the accidental release, and therefore one cannot give a unique answer for the consequences of a given release of material. By performing calculations for the whole spectrum of possible weather conditions one obtains *probability distributions* of numbers of early effects, late effects and other specified consequences.

To complicate matters further, a reactor system is so intricate that there is a whole spectrum of values for the quantities of radioactive materials that could be released in the event of accident, and variations over many orders of magnitude can be envisaged[6]. For each of these possible release quantities the probability distribution of consequences may be calculated, and then weighted by the frequency with which the particular release is estimated to be likely to occur. The sum of these distributions, taken over the whole range of possible releases each with its associated 'family' of consequences, constitutes an overall frequency-of-occurrence v. magnitude-of-consequence curve known as an fN line, examples of which are given in this paper. The presentation of the results of consequence calculations in this probabilistic fashion is unavoidable, partly because of the statistical nature of the processes occurring in the atmosphere, and partly because it is not possible to present the results of calculations of the possible releases from a nuclear installation other than in the form of a frequency-magnitude distribution. These fN lines provide information that is needed in order to form judgements on the acceptability of nuclear installations[31].

Table 4. Emergency Reference Levels for I-131, Cs-137, Ru-106 and Sr-90

Isotope	Critical organ	ERL of dose (rems)	ERL of cloud-dosage (Ci-sec/m^3)	ERL in milk (μCi/litre)
Iodine-131[a]	Thyroid	30	0.020	0.25
Caesium-137[b]	Whole body	10	1.5	5.5
Ruthenium-106[c]	Lung	30	0.014	–
Strontium-90	Bone marrow	10	0.05	0.15

[a]ERL of cloud-dosage makes allowance for iodine and tellurium in equilibrium proportions.

[b]External gamma radiation from caesium-137 deposition is more limiting than the ERL in milk.

[c]Ruthenium is released as insoluble ruthenium oxide, and does not appear in cows' milk.

Environmental consequences of notional accidental releases from nuclear power reactors

The radioactive substances in reactor cores are of two main types — the fission products, beta-gamma emitters mostly of short to medium-long half-life, and the actinides, mostly alpha emitters of very long half-life. The fractions of the various fission product or actinide elements composing the reactor inventory which are likely to be released in a hypothetical reactor accident depend, of course, on the type of reactor and the nature of the particular accident imagined. Information on the inventories associated with different reactors is listed in Reference 8, and can be obtained from various sources (References 6, 32 and 33). The reactor types considered here are Magnox Gas-cooled Reactors, Advanced Gas-cooled Reactors, Pressurised Water Reactors and the Commercial Demonstration Fast Reactor. Generally, fission product inventories do not vary much from one reactor type to another, for a given level of thermal power; however, the actinide inventory does so vary, the amounts of higher actinides in particular increasing considerably with burn-up.

Environmental impact of accidents to Magnox gas-cooled reactors In gas-cooled reactors such as Magnox the most serious kind of accident that has to be considered is a failure of the pressure circuit causing a rapid loss of coolant[34]. As in

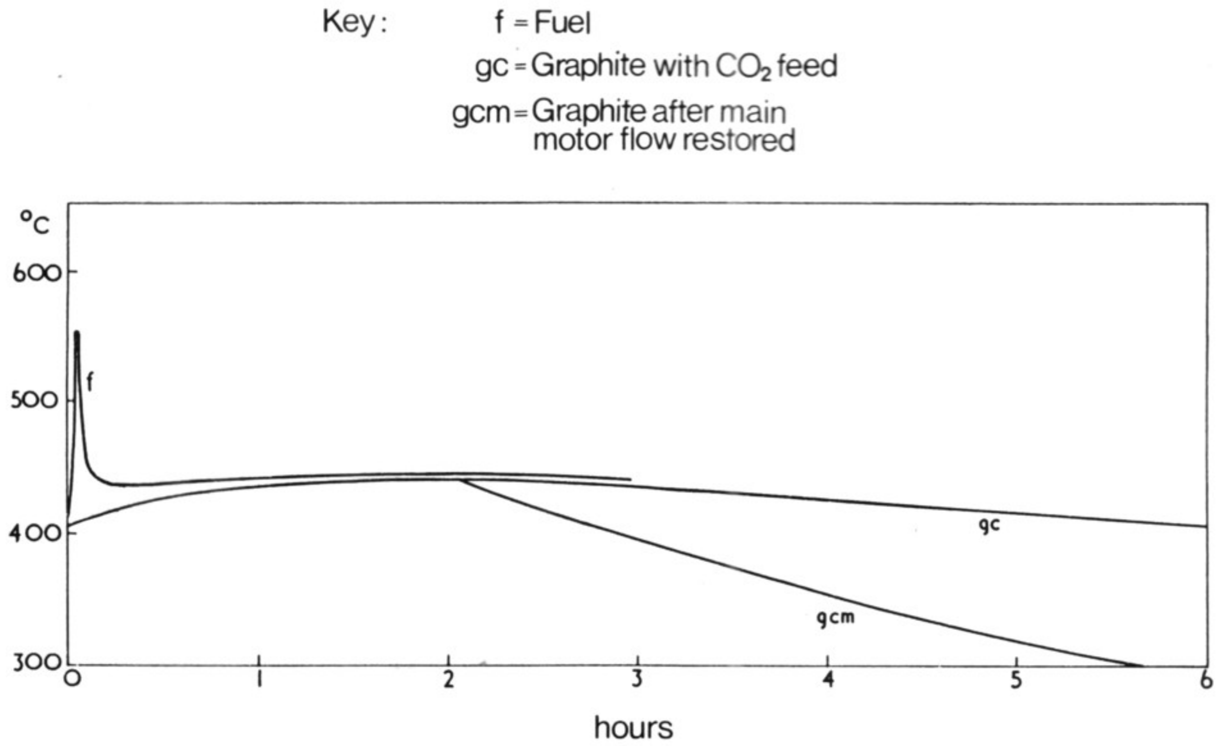


Fig. 2 Magnox reactor depressurisation accident: calculated temporal variation of fuel and graphite temperatures

all reactor types, very high reliability of shut-down is ensured by providing a number of automatic shut-down devices of different independent kinds to avoid some unforeseen fault being common to all. The nuclear reaction having beer quickly shut down, enough gas flow can be maintained even at atmospheric pressure to cool the fuel and prevent damage to it, provided that conditions in the channel are otherwise normal. In all UK gas-cooled reactors, ample emergency supplies of carbon dioxide are available to be fed to the reactor circuit and prevent ingress of air. In assessing the safety of Magnox reactors in steel pressure vessels with separate heat exchanger shells, the arbitrary assumption is made that a bottom inlet duct fractures, and that some air enters before the damaged circuit can be isolated. Thereafter carbon dioxide is fed in, gas flow is begun by the blowers driven by auxiliary motors and finally main-motor-driven gas flow is restored. It is an important and remarkable feature of Magnox (and AGR) reactors that they are able comfortably to survive sudden complete loss of coolant pressure. This is illustrated by a typical temperature transient taken from Reference 35, displayed in Figure 2. This is for a Magnox reactor with well-irradiated fuel (high fission product after-heat) and long-irradiated graphite. Appropriate levels of Wigner energy and the effects of irradiation and impurity-enhanced graphite oxidation rate have been taken into account in the calculations. It will be seen from this example that the design ensures safe clad temperatures are not normally exceeded in the first few minutes when fuel internal temperatures equalise radially across the fuel rod, gas cooling being temporarily diminished. Temperatures would remain under control for several hours with only auxiliary-motor-driven gas flow, and when main-motor-driven flow is restored temperatures would fall very rapidly to entirely safe levels. The later Magnox reactors have prestressed concrete pressure vessels which contain the reactor core and all the heat exchangers: any accidental breach in the gas circuit, if it occurred, would probably be very small and the consequent variations of reactor temperatures would be still easier to control. The conclusion drawn from studies of this kind is that if an accidental depressurisation of a Magnox reactor were to occur, by far the most probable outcome would be no release of fission products or actinides at all, and therefore no environmental impact.

Safety studies show that for the earlier steel pressure vessel Magnox reactors, should a sudden loss of coolant pressure occur there is a small chance, less than 1 in 100, of a single channel melt-out occurring in the most highly-rated fuel channel. This and other aspects of gas-cooled reactor accidents have been discussed by Macdonald *et al* of CEGB in Reference 36, where experimental evidence is reviewed and theoretical aspects are studied using the CEGB reactor safety analysis code WEERIE[30]. Macdonald and his co-workers group the fission products into broad classes of volatility, in which for example iodine and tellurium are considered volatile, caesium and ruthenium are mid-volatile (unless there is air present, when they are classified as volatile), and strontium and the rare earths are considered non-volatile. The release fractions from fuel to coolant are assumed to be 10 per cent, 1 per cent and 0.1 per cent respectively for a channel melt; for a channel fire they are increased by a factor of five. Macdonald *et al* state[36] that for the assumed releases the ERL of inhalation dose (by implication a thyroid dose mainly from iodine and/or a lung dose mainly from ruthenium and other beta emitters) is estimated to occur at 1½ miles for the steel vessel Magnox reactor and at ⅔ mile for the concrete vessel Magnox reactor. It may be inferred that releases broadly in the range 10-100 Ci iodine 131 are under consideration. The deposition of released activity within the reactor coolant circuit and containment is an important factor determining the discharge to atmosphere, and in the WEERIE calculations this is taken into account using elemental plate-out factors which for the non-gaseous fission products are assumed to lie in the range 0.01-0.15 min^{-1}; these values are typical of those observed in operating gas-cooled reactors under channel melt-out conditions[37,38]. Other factors which have been investigated include the reduction in inhalation doses at short distances downwind due to the entrainment of effluent in the wake of the reactor building. This is illustrated in Figure 3, which shows representative dose versus distance curves calculated using the WEERIE code for a Magnox depressurisation accident accompanied by a single channel melt-out. The dashed curves show the effect of building entrainment as predicted by a simple virtual source model, which wind tunnel experiments have demonstrated may be appropriate in many circumstances[36]. Figure 3 shows that, for the accident and dispersion conditions considered, the inhalation dose to the thyroid from the radioactive iodine could be 1 ERL out to 450m downwind at most. Other environmental impacts to be considered include contributions to thyroid dosage from ingestion of cow's milk (in practice this would mean the distance downwind to which prohibition of milk supplies should extend) and from ingestion via routes other than milk e.g. via green vegetables or hand contamination. The distances at which these effects might independently give rise to 1 ERL of thyroid dose can be calculated, and the picture emerges, supplementing the information contained in Figure 3, of a prohibition for a few weeks on the sale and consumption of milk from farms within about 3 km downwind of the reactor, and possibly of a temporary warning about general iodine contamination and against eating locally grown green vegetables for members of the public, if any, who elect to remain within perhaps 150m downwind of the reactor. These and any other aspects of the 'environmental emergency' would be confidently handled and contained by the elaborate, carefully planned and frequently practised emergency arrangements at CEGB nuclear power stations, which have been described by Orchard and Walker in Reference 39. Similar emergency arrangements are made and exercises carried out at SSEB and UKAEA/BNFL nuclear power reactor sites.

Environmental impact of accidents to Advanced Gas-cooled Reactors The Advanced Gas-cooled Reactor (AGR) is a development of the Magnox Reactor, allowing rather higher fuel ratings and burn-up through the use of uranium oxide fuel in assemblies of stainless steel clad pins and re-entrant coolant flow through the core. All the AGRs operated by the UK Generating Boards have prestressed concrete pressure vessels. A sudden loss of coolant pressure due to an accident would be most unlikely to lead to fuel melt-out, and the maximum transient fuel temperature would be several hundreds of degrees Celsius below the melting point of stainless steel. There is a possibility, however, of a few pins of highest rating puncturing under internal fission gas pressure at the clad temperatures reached transiently, external gas pressure being reduced. A small percentage of the inventory of gaseous and volatile fission products in the pins will have diffused to the fuel-clad interspace during normal operation and will be available for release. The manner and magnitude of fission product release from fuel to coolant in such conditions has been much studied (e.g. Reference 38) and their deposition in the reactor gas circuit must also be taken into account, as mentioned above (see also Reference 36). The estimated size of release to the atmosphere after a loss-of-pressure accident is generally less than 10 Ci iodine 131. The only environmental impact would be a temporary ban on consumption of cows' milk up to about a mile downwind. Partly as a result of these favourable environmental features some AGRs are located quite close to urban areas in the United Kingdom. However, there is, as yet, an absence of published studies of AGR (and Magnox reactor) accidents comparable in scope to the USNRC studies of water reactor safety[6].

Environmental impact of accidents to Pressurised Water Reactors The development and consequences of hypothetical accidents to PWRs were analysed on a probabilistic basis in the USNRC Reactor Safety Study[6]. Of these accidents, that designated PWR9 approximates to the design basis accident (d.b.a.) or maximum credible accident (m.c.a.), and is perhaps the analogue of the depressurisation accident for the Magnox and AGR reactors described above. If, as in PWR9, there were an accidental pipe break in the primary pressurised coolant circuit of a PWR, the greater part of the water would flash off as steam, carrying some water along with it. Steam is a very poor coolant compared to liquid water, and if nothing were done fuel would melt. In the PWR9 accident description, the emergency core cooling system comes into action automatically as designed and cooling water is quickly conveyed to the fuel. However, a small percentage of the inventory of gaseous and volatile fission products which will have collected in the fuel clad interspace is assumed to escape from fuel pins punctured by internal fission gas pressure. The environmental impact is minimised by the containment which is designed to contain the steam pressure. This would be high initially and some leakage of fission products would

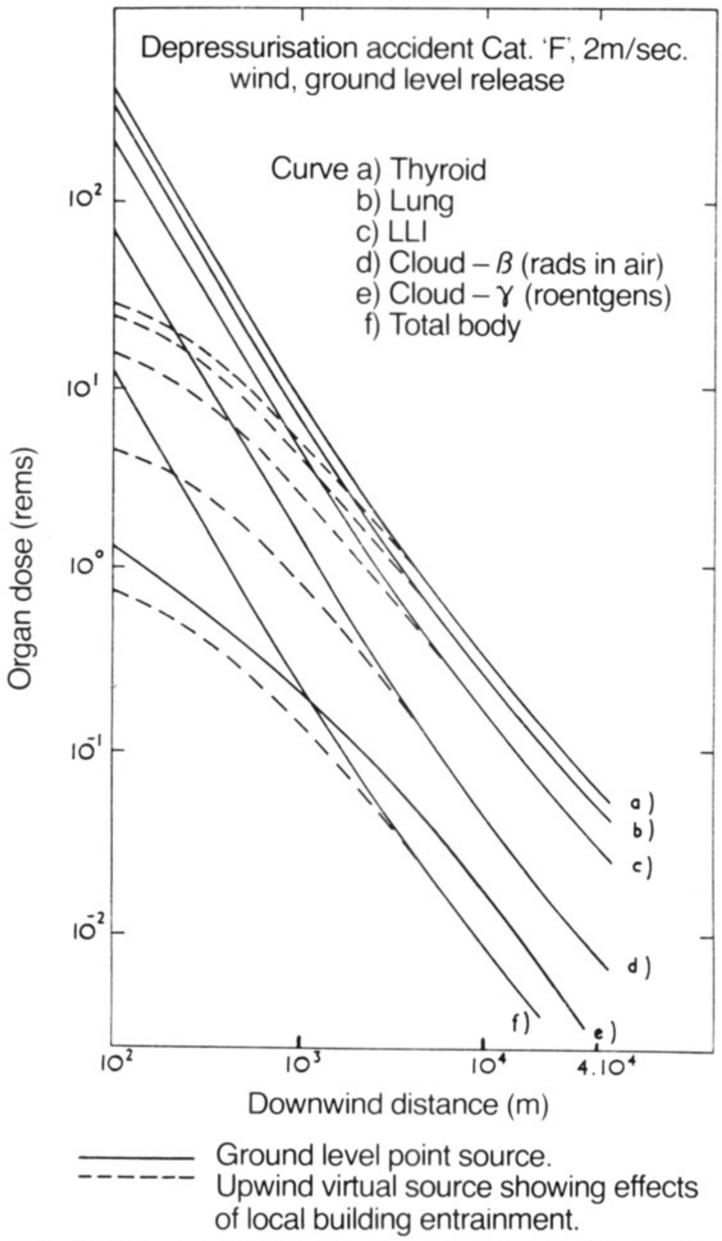
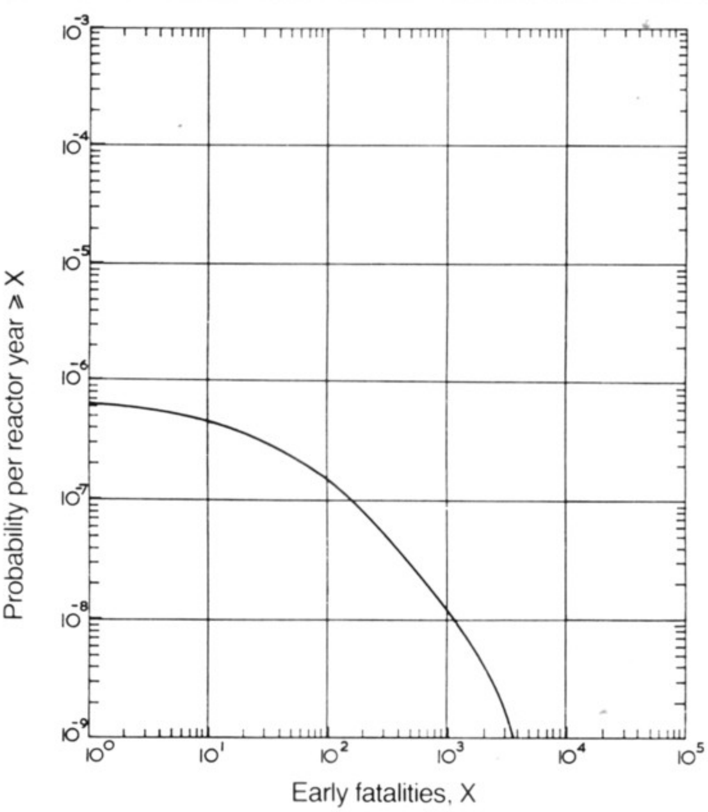
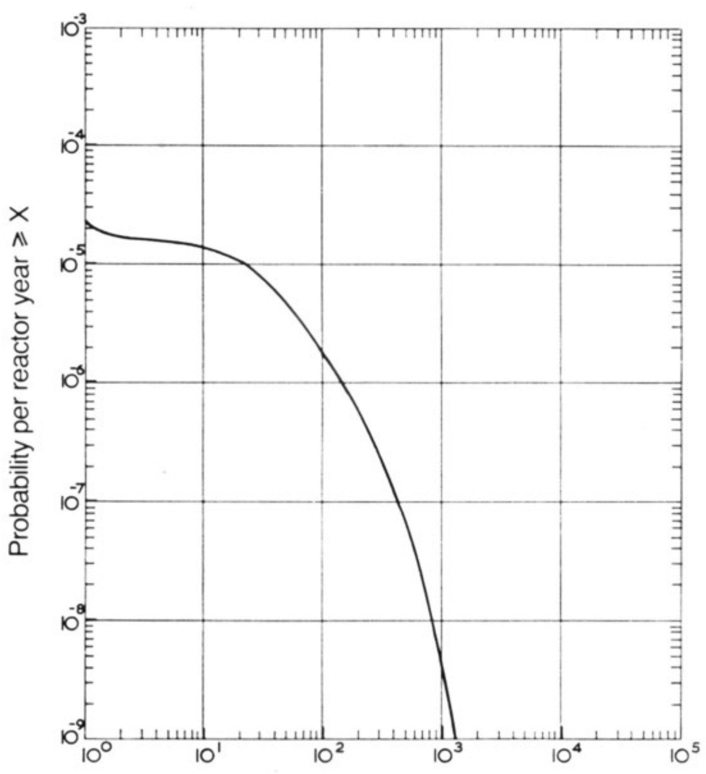


Fig. 3 Magnox reactor depressurisation accident with single channel melt-out: integrated inhalation and cloud doses



Note: Approximate uncertainties are estimated to be represented by factors of 1/4 and 4 on consequence magnitudes and by factors of 1/5 and 5 on probabilities

Fig. 4 Probability distribution for early fatalities per reactor year (Pressurised Water Reactor)



Note: Approximate uncertainties are estimated to be represented by factors of 1/6 and 3 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.

Fig. 5 Probability distribution for latent cancer fatality incidence per reactor year (Pressurised Water Reactor)

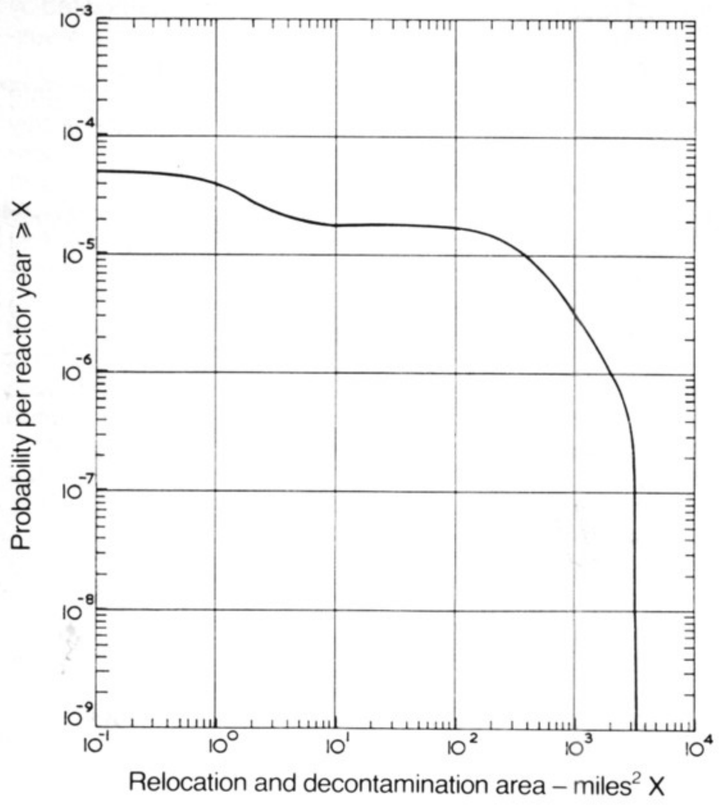
occur to the atmosphere. However, the containment water sprays would come into action to reduce the steam pressure and terminate the leakage after about half an hour. The release to atmosphere would consist of about 10 Ci iodine 131 with similar small quantities of other gaseous and volatile fission products. The release foreseen for this accident is thus similar to that envisaged for the steel pressure vessel Magnox reactor. It is perhaps partly for this reason that it is believed in some quarters that if PWRs are adopted in the United Kingdom they should at first be constructed on sites similar to those occupied by Magnox reactors.

The environmental impact of more severe PWR accidents was also analysed in the USNRC study. In these accidents, at low levels of probability, it is envisaged that engineered safeguards such as the emergency core cooling system and/or the containment spray system fail to come into operation as required following primary coolant circuit depressurisation. Environmental consequences are thus larger. As an example of this class of severe but highly improbable accidents, accident type PWR2 is discussed briefly below. The expected frequency of occurrence of this accident was estimated to be just less than 1 in 10^6 years per reactor, although one surmises that this figure would depend somewhat on design details of the particular PWR in question. Some experts in the UK consider that the true frequency of this class of event is less than 1 in 10^7 years per reactor. The main features of the sequence of events imagined to culminate in this accidental release, which is very large, are as follows. The category 2 releases are associated with the failure of core-cooling systems, leading to core melting, concurrent with the failure of containment spray and heat-removal systems. Containment rupture would be caused by overpressure due to hydrogen burning and steam pressure. A substantial fraction of the contents of the breached containment would be released in a 'puff' over a period of about 30 minutes, with the remaining fraction continuing to leak out at a relatively low rate thereafter. The total release would include 6×10^7 Curies of iodine 131, along with about $2{\cdot}5 \times 10^6$ Curies of caesium 137. Because of the presence of hot pressurised gases in the containment at the time of failure, this release would be characterised by a relatively high rate of release of sensible heat.

The USNRC study made use of nine categories in all to represent the spectrum of possible releases from PWRs. An expected frequency of occurrence was calculated for each of the associated release inventories, and the consequences were estimated in each case. Figures 4, 5 and 6 are reproduced from the report as representative examples of the results of the study. These figures show the probability per reactor year versus the magnitude of the consequence for three specific effects, namely early fatalities, latent fatalities, and size of the area of land requiring decontamination (principally due to deposited caesium). As can be seen from Figure 4 the frequency of an accident that results in more than 10 early fatalities is about 5×10^{-7} per reactor year; accidents involving 100 or more such fatalities are predicted to have a frequency of about 10^{-7} per reactor year.

The cumulative frequency distributions displayed in these graphs reflect the particular characterists of the population distributions and weather patterns appropriate to the United States. In view of the recent decision to consider the option of building PWRs on UK sites, it is necessary to examine PWR accident consequences in the context of UK conditions; studies are currently under way at SRD to investigate the topic.

The numbers of people that could be affected by a given release would be rather larger in the UK, compared with the USA figure, because of the higher population density. However, this would be counterbalanced by a decreased probability of occurrence of class F weather (the least favourable in



Note: Approximate uncertainties are estimated to be represented by factors of 1/5 and 2 on consequence magnitudes and by factors of 1/5 and 5 on probabilities

Fig. 6 Probability distribution for decontamination areas per reactor year (Pressurised Water Reactor)

the context of dispersion of hazardous material) in the UK.

The Generic Safety Study published in July 1977 by the Nuclear Installations Inspectorate states that "the Inspectorate consider that there is no fundamental reason for regarding safety as an obstacle to the selection of a Pressurised Water Reactor for commercial electricity generation in Britain"[40].

Environmental Impact of Accidents to Fast Reactors† The safety case for the UK commercial demonstration fast reactor (CDFR) is based on the inherently advantageous characteristics of the sodium-cooled pool-type system. The use of an efficient, low pressure coolant acting as a large heat sink, together with a highly reliable shut-down system, reduces the risk of accident to very low levels.

Re-fuelling accidents probably offer the most easily envisaged route for the escape of significant quantities of fission products to the atmosphere of the secondary containment (if not to the free atmosphere), although present designs now make this exceedingly unlikely. The situation usually examined is one in which an error occurs while an irradiated fuel sub-assembly is being transferred from the coolant vessel or circuit to the irradiated fuel examination booths or to the irradiated fuel store. As a result, the sub-assembly could overheat and melt, releasing gaseous and volatile fission products. At the time of reactor shut-down a typical CDFR sub-assembly would contain $\sim 2 \times 10^5$ Ci of iodine 131 and $\sim$5000 Ci of caesium 137, but since movement of the sub-assembly out of the coolant would be preceded by a stay of about 100 days in the coolant clear of the reactor core, only some 50 Ci of iodine 131 would remain. If this and the 5000 Ci of long-lived caesium 137 should escape into the secondary containment, its pathway to the atmosphere would lie through a battery of sprays, HEPA* filters and charcoal filters (any actinides and nonvolatile fission products becoming airborne as a dust would be trapped by the HEPA filters). The radioactive material released to the atmosphere, assuming all these safety features operate correctly, would contain less than 1 Ci of iodine 131 and 1-10 Ci of caesium 137: this would lead to very small environmental effects, and it can be shown that it would be expected that significant levels of dose would not be reached beyond the boundary fence.

Another possible accident could involve localised fuel pin damage. In this case volatile fission products such as iodine 131 would be released from the fuel but would be efficiently absorbed by the sodium coolant — the affinity of sodium for certain fission products, leading to their retention in the primary circuit, is an additional safety feature of the fast reactor. Minor damage to a fuel pin would thus lead to a bubble, containing gaseous fission products only, escaping to the blanket gas. Any release to the atmosphere would be trivial.

Considerations such as these lead to confidence that it should be possible to operate fast reactors to at least the standard of safety already achieved in thermal reactor operations. The only safety feature that is more difficult to establish for fast reactors than it is for thermal reactors is the effect of a highly improbable nuclear excursion that might take place, for example as a result of a geometrical compaction of the core giving a reactivity increase. The whole design concept of the reactor seeks to avoid whole core accidents but these still attract much attention in the safety study of the reactor. In these hypothetical accidents, complete loss of flow or some arbitrarily large increase of reactivity is assumed to occur and in addition the highly reliable automatic protection system is assumed to fail and cause the core to melt down. The fuel could then be heated to its boiling point and the boiling of the fuel and the heating of the gases within it will cause core expansion which will finally terminate the excursion. Even in such a violent excursion as this the total energy released will still be relatively small and will be unlikely to breach the containment, although it will never be possible to calculate the exact course of such speculative events. There is, however, sufficient evidence to show that the probability of whole core accidents is acceptably low; nonetheless, it is the intention that CDFR will have a strong containment. This containment will be provided by a thick prestressed concrete pressure vessel with a strong roof supporting the reactor components, and an outer secondary containment building to prevent the escape of any radioactivity which finds its way into the space above the operating floor. This structure will have a very high probability of completely containing any accident, though in scientific and engineering terms it cannot be claimed that the containment of all whole core accidents can be absolutely guaranteed, and it is reasonable to look at the consequences that could arise should a whole core accident result in a breach of the containment and a release of activity.

Recently, the UK Nuclear Installations Inspectorate commissioned the National Radiological Protection Board to undertake a 'theoretical study of the possible outcome of a range of events extending to extremes in which all protective measures have failed'[33]. The introduction, written by the NII, speaks of a 'sudden and very serious release' which could only take place 'if the containments failed catastrophically'. NRPB consider releases to the atmosphere containing up to

†In this section *liquid metal cooled fast breeder reactors* (LMFBRs) only are considered since, in the UK and elsewhere, R and D programmes are almost exclusively devoted to these and not to a possible alternative, the gas-cooled FBR.

*High Efficiency Particulate Air Filters.

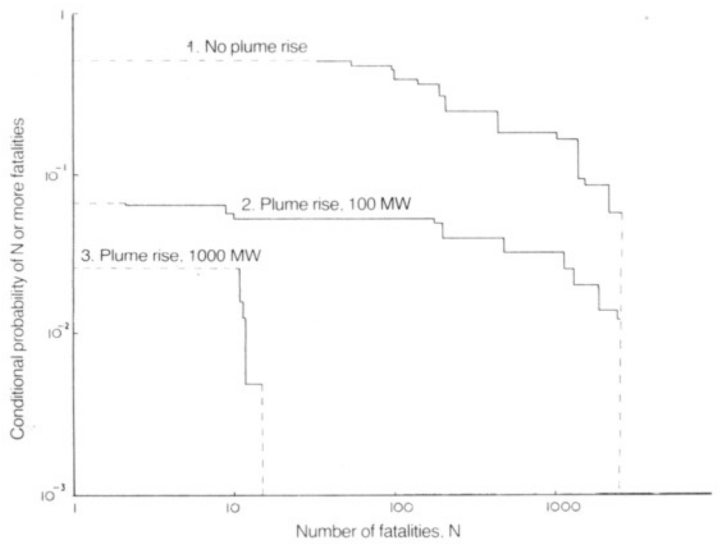


Fig. 7 Conditional probability of early death assuming the escape to the atmosphere of 5 per cent of the core plus volatiles from a fast reactor, 1000 MW(e), on a 'remote' site in the UK

10 per cent of the core plus the volatiles from the remainder of the core, though there is no suggestion that a whole core accident would actually result in such a level of release. The NRPB report concentrates on early deaths, early morbidities, cancers and hereditary effects. Taking the assumption that 5 per cent of the core of a 3000 MW(t) fast reactor is vaporized and escapes to the atmosphere, together with volatile fission products from the remainder of the core, typical results from Reference 33 are as follows: on a remote site, there could be 300 early deaths, 200 morbidities, 3900 deaths from cancers and 60 or so hereditary effects within 30 years (for a definition of the various forms of hereditary effects see Reference 7).

The figures quoted above refer only to category C-D, 'average' weather conditions, which alone are considered by NRPB. However, it has been noted above that, for a given release, the results should properly be presented as a probability distribution of consequences. In Figure 7 the *probability distribution* of early deaths shown as curve 1 is obtained assuming that the 5 per cent release described above occurs from a reactor on a remote site. This curve was calculated using the SRD computer code TIRION assuming that there is no plume rise and that there is early evacuation of people from areas heavily contaminated by deposited γ —emitters.

It is possible to demonstrate that the calculated early consequences of a large release from a fast reactor can probably be considerably reduced if proper account is taken of plume rise, an aspect to which only limited attention is given in the NRPB study. The burning of several tonnes of sodium could liberate 100-plus GJ of heat so that rates of heat release of 100 or 1000 MW can in principle be sustained for some 30 or 3 minutes respectively. Figure 7 shows that the calculated numbers of early deaths are very sensitive to assumptions about plume rise. The effect of plume rise on the probability distributions of cancers and of unacceptably contaminated areas of land is much less marked, however. The areas likely to be contaminated in the long term by deposited γ — emitters are comparable to those predicted for the most severe of Rasmussen's postulated PWR accident sequences[6] since, in both cases, of the order of 10^6 Ci of caesium 137 are assumed to escape from the reactor. For the fast reactor case, the areas significantly contaminated by deposited actinides, which are hazardous when resuspended by the wind, are larger than for the biggest of the PWR sequences, partly because the fast reactor core contains more actinides than does the PWR, and partly because in the most severe of these hypothetical whole core incidents, a relatively large percentage of the inventory of non-volatiles is assumed to escape to the atmosphere.

To conclude, dispersion of a substantial fraction of a fast reactor core (or of a thermal core) would cause a large number of casualties. Continuing developments of theoretical studies of the course of the whole core accidents and their aftermath will enable the designers of the UK's CDFR to ensure that the frequency of occurrence of accidents severe enough to release significant quantities of radionuclides to the atmosphere will be low enough to satisfy the high standards practised by the nuclear industry. Examples of these standards are the guidelines recently suggested by G.H. Kinchin, the Director of the UKAEA's Safety and Reliability Directorate[31].

The nature of risk

Discussion of this topic is notoriously fraught with difficulties arising from differences of opinion over what degree of risk is acceptable, and how different risks are to be compared. In order to engage in a sensible dialogue on this subject it is necessary to distinguish quite clearly at the outset between two aspects, namely the *measurement or estimation* of risk, and the *acceptability* of risk. Of the two, it is the acceptability of risk that poses the more intractable problem, since in the end this is an issue which by its nature must be decided through the democratic process at Government level, whereas the measurement of risk is susceptible to a satisfactory degree of quantitative description. Decisions on the acceptability of risk can be more rationally achieved if there is a strong basis of quantitative measurement of risk. In view of these characteristics the following sections are mainly devoted to the problem of the measurement of risk, but they also contain some indicators of the nature of the difficulties associated with the acceptability of risk, in order to maintain the distinction between the two. Some readers may consider it self-evident that this division should be maintained in the practice of risk management. However, it is by no means universally accepted that this should be the case (see, for example, W.D. Rowe, Reference 41).

Various ways of expressing risk have been devised, each suited to the particular activity with which the risk is associated. Although these have their merits in their parti-

Table 5. Individual death risks in Great Britain

ICD* Nos	Cause of death	Risk per person per year
000-999	All causes	1.18×10^{-2}
000-799	Natural causes	1.14×10^{-2}
390-458	Disease of circulatory system	6.17×10^{-3}
410-414	Ischaemic heart disease	3.12×10^{-3}
140-239	Neoplasms	2.47×10^{-3}
800-999	Other than natural causes	4.42×10^{-4}
800-949	All accidents	3.25×10^{-4}
810-823	Road accidents	1.22×10^{-4}
880-887	Falls	1.11×10^{-4}
890-899	Fires	1.6×10^{-5}
910	Drowning	1.2×10^{-5}
800-807	Rail transport	3.3×10^{-6}
925	Electrocution	2.5×10^{-6}

*International Classification system for causes of death.

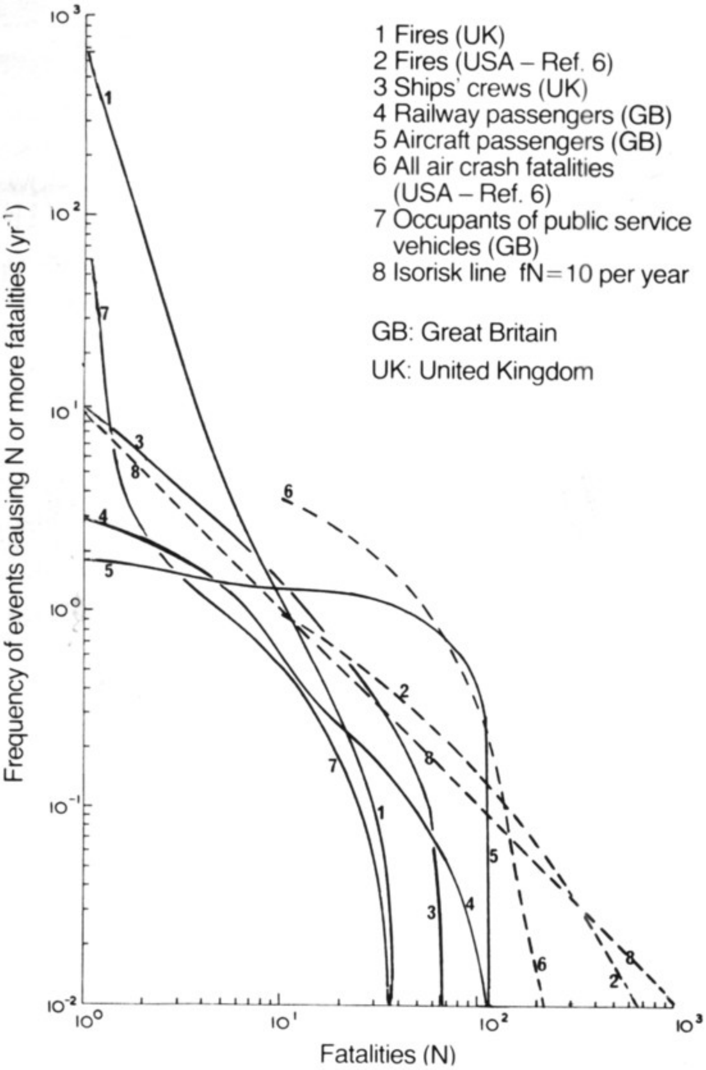


Fig. 8 The incidence of multiple fatality accidents

cular applications, there is considerable difficulty in comparing different measures of risk, since the choice of a common unit is a matter of some debate. Rather than attempt to unravel this contentious issue, and perhaps thereby confuse the matter further by adding yet another scheme of interpretation, it is simpler to reduce the problem to the consideration of two concepts of risk, namely *individual risk*, which is the average probability of death per person per year (calculated as the number of deaths per year from a particular cause divided by the total population), and *community risk*, which expresses the frequency of occurrence of incidents involving multiple fatalities. In order to gain a perspective of the risks to which people are exposed it is instructive to look at individual and community risk data for the United Kingdom. Readers of the Rasmussen Report will be familiar with the tables and graphs of these risks presented in that study, based on data and predictions for the United States. These figures have been used by many authors in discussions of risk measurements as though they applied to any comparable industrialised nation. It is perhaps worth noting that there are substantial differences in the risk data for the UK compared with the USA, as evidenced in two recent UKAEA reports[42,43]; the overall individual risk of accidental death in the USA is about twice the UK value, with some causes displaying risks that are as much as three times higher in the USA compared with the UK. Table 5 and Figure 8 are reproduced from References 42 and 43. To give some perspective to the individual risk data in Table 5 it is instructive to note that accidental death constitutes only 2.75 per cent of the overall risk from *all causes*, and that about two-thirds of the overall *accidental* death risk arises from fatalities due to road accidents and falls. Figure 8, showing frequency of occurrence of incidents resulting in N or more fatalities for five different causes in the UK, displays some features that require comment. It will be noted that there is a relatively high risk of death through fires in the N = 1 to 10 range. This may indicate that a greater degree of care and regulation is applied to fire safety in premises where large numbers of people assemble, as distinct from domestic premises where less control may be exercised. The distinctly higher risk in the aircraft passengers line in the range N = 10 to 100 doubtless reflects the preponderance of aircraft carrying this number of passengers. For ships' crews, rail passengers and public service vehicle occupants the data correspond approximately to lines of equal risk with the risk product fN being typically about 10 yr^{-1} over much of the range (i.e. the product fN does not vary much with N), whereas the fire and aircraft lines both depart substantially from this behaviour. This is referred to again in the discussion of the acceptability of risk.

The use of individual risk and community risk as indicators involves certain assumptions and qualifications. It is only fair to acknowledge these, and mention is now made of some of the facets that should be borne in mind in interpreting these data. Concerning individual risk, the assumption in the definition is that the population at hazard is the total population. This is a simplifying assumption that has to be examined in some detail. Obviously some occupations are attended with a higher risk than others and these departures from average values can be very large indeed, so that the risk associated with a particular cause of death can be quite different for different sections of the community. Again, it is clear that some classes of risk are significantly underestimated by assuming that it is the total population that is exposed to the hazard; for example not everyone travels by road, or by rail, and any individual may choose to forego these forms of travel, thereby eliminating that contribution to his total individual risk. Further, people that do engage in a particular pursuit do not generally share the risk equally among their number. In activities of this sort, where the risk can reasonably be argued to increase in proportion to the extent to which the individual engages in the pursuit, other things being equal, it is appropriate to express the risk in terms of, for example, deaths per person per mile travelled, or deaths per person per hour of activity. This serves to illustrate the difficulties encountered when trying to compare risks. Although the definition of individual risk adopted here does not overcome these problems, it does have the virtue of simplicity, and its assumptions are unambiguous. With these qualifications in mind the reader may gain a useful insight into the spectrum of individual risk catalogued in Table 5.

In considering the community risk, as represented by the fN lines of Figure 8, one needs to be aware of the limitations imposed on their significance by the 'patchiness' of the data. In addition, safety standards and practices may well change over the data period considered, and such changes do not manifest themselves in the fN lines (for example, it is noted in Reference 43 that over the last twenty years there has been a reduction by a factor of about three in the annual total number of accidental deaths incurred in the operation of the railways). Given these limitations the concept of the fN line provides a useful basis for comparison of risks for accidents involving multiple fatalities, which undoubtedly have a special significance in the perception of risk.

The foregoing survey of individual and community risk provides information on the magnitudes of the contributions made by various activities to the overall burden of risk. This does not reveal anything about people's willingness to accept these risks, except insofar as the fact that they are allowed to continue to exist implies some degree of acceptance. However, something useful can be deduced from the fact that where there is a risk of death approaching 10^{-3} per year, steps are usually taken to reduce this if possible — hence the current concern over the death toll due to traffic accidents. As the risk diminishes, concern and countermeasures are less in evidence, and for risks less than about 10^{-6} or less per year it seems that the individual does not think it necessary to take steps to reduce the risk further. This suggests that society in practice regards individual risks of about 10^{-6} or less per year as acceptable. It is often argued that a distinction needs to be made between voluntary and involuntary risks, and it is clearly reasonable that this should be the case, difficult though it is in some instances to draw such a clear distinction. However, this argument becomes less forceful for risks that are of such a small magnitude that the public generally are unaware of them at any significantly conscious level.

Many authors, in discussing the concept of the fN line as a measure of community risk, have pointed out that an industry that gives rise to, say, 100 deaths one at a time over a period of ten years is more readily tolerated than one causing 100 deaths all at once every ten years, even though the two are equal in terms of the annual average death toll. It has been said that the reason for this decrease in the acceptability of equal risks as N increases is probably that an incident causing 100 deaths in a single community is much more disruptive than 100 deaths spread over a longer time, and over a wider community. Does this mean that in general the acceptability of community risk falls as N increases? Referring to the aircraft passenger fN line in Figure 8, there is a very much higher risk in the N = 10 to 100 range than in the N = 1 to 10 range, and yet practice suggests that this is in fact acceptable. Although one would hesitate to draw any conclusions from this, it does demonstrate the powerful influence of economics and perceived benefit as factors that affect our willingness to be exposed to a given risk.

Risk criteria for nuclear reactors

In view of the desirability of comparing nuclear power plant risks with others to which we are exposed it is logical to express design criteria in terms of individual and community risk criteria. Accordingly the UKAEA Safety and Reliability Directorate has been developing such criteria for use as design targets for power reactors. Because of the potential for both early and delayed fatalities as a result of radiation exposure, two criteria for both individual and community risk have been proposed. The rationale behind these proposals is discussed by their author, G.H. Kinchin, in Reference 31. For individual risk it is suggested that 10^{-6} per year should be the limit for early deaths, and 3×10^{-5} per year for delayed deaths. For community risk it is proposed that the risk product fN should take the value 10^{-4} per year for early deaths, and 3×10^{-3} per year for delayed deaths.

The intended interpretations of the community risk criteria, as discussed in Reference 31, is that the value of the ordinate $p^{(N)}$ represents the limiting probability per year (or frequency) of producing a number of fatalities roughly in the range N/3 to 3N, or approximately a factor of 10 spanning the number N. These criteria are therefore non-cumulative forms of fN lines; they are displayed in Figure 9 together with their equivalent cumulative forms, which show the limiting frequency of incidents producing N or more fatalities. It will be seen by comparing these cumulative forms of Kinchin's criteria with the cumulative fN lines for actual accidents in Figure 8 that they fall many orders of magnitude below the fN product for multiple fatality accidents in the UK, for which values of the product fN of about 10 per year are representative.

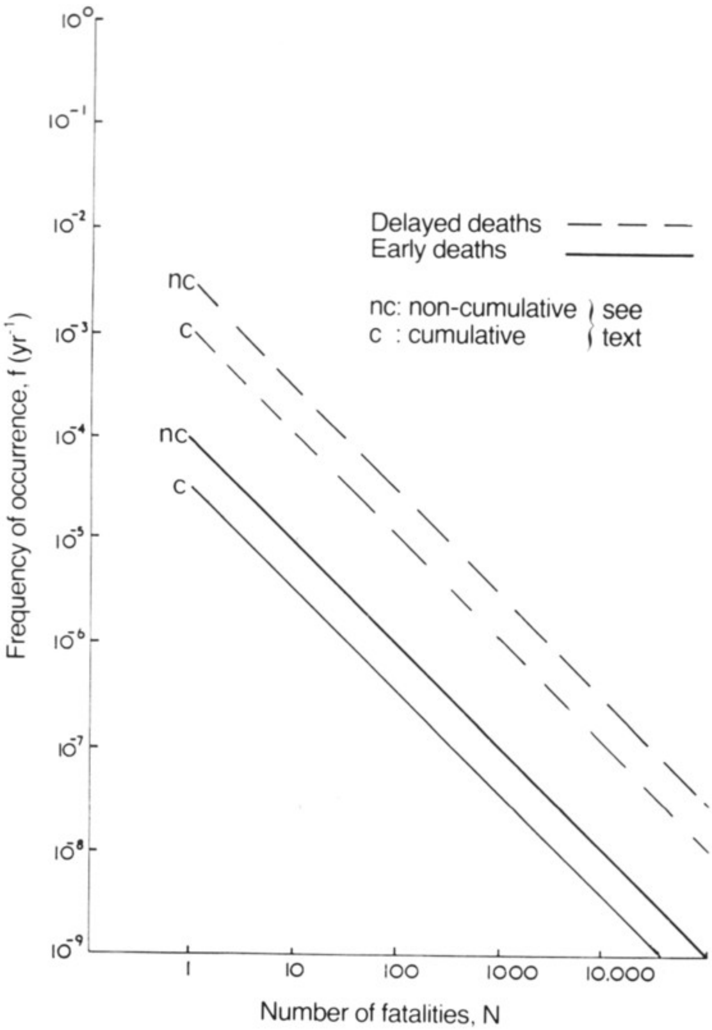


Fig. 9 Proposed community risk criteria

To illustrate the level of risk implied by the individual early death criterion of 10^{-6} per year, one may consider the following: suppose that an individual decides to reduce his risk of early death from a nuclear power plant accident by moving house away from the plant, and that in consequence he has to drive a somewhat greater distance to get to work. From Table 5 the individual risk of death from road accidents is 1.22×10^{-4} per year in the UK. The average annual mileage covered by the British motorist is about 10 000 miles, so the risk may be expressed as $(1.22 \times 10^{-4})/10^{4} = 1.22 \times 10^{-8}$ per mile per year. It follows that the risk of 10^{-6} is equivalent to driving an extra 82 miles per year, which corresponds to an extra 300 yards per journey to or from work for a man working a five day week for 48 weeks a year. Thus, if moving away from the nuclear power plant increases the distance to work by more than 300 yards, it is safer to live next to the plant. Put in these terms, most people would find this risk acceptable.

Conclusions

In this paper consideration has been given to the consequences that could be suffered in the event of accidental releases of radioactive material from nuclear power reactors. These consequences are examined in terms of early and late biological effects on man, and contamination of areas of land. Accidents that could conceivably lead to such outcomes are of low probability of occurrence. Defining risk as

"Suppose that an individual decides to reduce his risk of early death from a nuclear power plant accident by moving away from the plant . . . In UK conditions, if this increases his distance to drive to work by more than 300 yards it is safer for him to live next to the plant. Put in these terms, most people would find this risk acceptable."

the product of the magnitude of the consequence and the expected (or limiting) frequency of occurrence, one may compare these potential risks with other risks actually incurred in the UK, and target risk criteria can be devised. Measured in terms of these definitions, the risk of accidents to nuclear power reactors is estimated to be very small indeed.

References

1. Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Annals of the ICRP, Vol. 1, No. 3. 1977, Pergamon Press.

2. G.A.M. Webb, 'Radiation Exposure of the Public — the Current Levels in the United Kingdom' NRPB Report NRPB-R24.

3. G.J. Hunt *et al*, 'Fallout in Rainwater and Airborne Dust — Levels in the UK during 1975' NRPB Report NRPB-R49, (1976).

4. F.E. Taylor *et al*, 'The Data submitted by the United Kingdom to the United Nations Scientific Committee on the Effects of Atomic Radiation for the 1977 Report to the General Assembly' NRPB Report NRPB-R47, (1976).

5. United Nations Scientific Committee on the Effects of Atomic Radiation 'Sources and Effects of Ionizing Radiation' 1977 Report to the General Assembly, particularly Annex C pages 115-165.

6. United States Nuclear Regulatory Commission, 'Reactor Safety Study' WASH-1400, October, 1975.

7. H. Smith and J.W. Stather, 'Human Exposure to Radiation following the Release of Radioactivity from a Reactor Accident: a Quantitative Assessment of the Biological Consequences' NRPB Report NRPB-R52, (1976).

8. J.R. Beattie, R.F. Griffiths, G.D. Kaiser and G.H. Kinchin, 'The environmental impact of radioactive releases from accidents in nuclear power reactors' UKAEA/SRD Paper to Nuclear Energy Panel of UNEP/IAEA, 1978.

9. International Commission on Radiological Protection, 'The Evaluation of Risks from Radiation' ICRP Publication 8, Pergamon Press 1966.

10. G.W. Dolphin and W.G. Marley, 'Risk Evaluation in Relation to the Protection of the Public in the Event of Accidents at Nuclear Installations' UKAEA Report AHSB (RP) R93, (1969).

11. Advisory Committee on the Biological Effects of Ionizing Radiation, U.S. National Academy of Sciences/National Research Council, 'The Effects on Populations of Exposure to Low Levels of Ionizing Radiation', BEIR Report Washington D.C., (1972).

12. Medical Research Council, 'The Toxicity of Plutonium', HMSO London (1975).

13. M.C. Thorne and J. Vennart, 'The Toxicity of Strontium 90, Radium 226 and Plutonium 239' Nature, 263, 553, (1976).

14. R. Scott Russell, 'Radioactivity and Human Diet' Ch. 14, Pergamon Press (1966).

15. H.J. Gale *et al* 'The Weathering of Caesium 137 in Soil' UKAEA Report AERE R4241 (1963).

16. J.R. Beattie and P.M. Bryant, 'Assessment of Environmental Hazards from Reactor Fission Product Releases' UKAEA Report AHSB(S)R135 (1970).

17. ICRP 'Recommendations of the International Commission on Radiological Protection' (Adopted September 17th, 1965) ICRP Publication No. 9, paras 29-39, Pergamon Press (1966).

18. Medical Research Council, 'Criteria for Controlling Radiation Doses to the Public after Accidental Escape of Radioactive Material'. HMSO London (1975).

19. D.H. Slade, (Ed). 'Meteorology and Atomic Energy', US Atomic Energy Commission/Division of Technical Information Report TID-24190 (1968).

20. F.A. Gifford, 'A Review of Turbulent Diffusion Typing Schemes', Nucl. Safety 17, 68, (1976).

21. R.P. Hosker, 'Estimates of Dry Deposition and Plume Depletion over Forests and Grassland' in 'Physical Behaviour of Radioactive Contaminants in the Atmosphere' IAEA STI/PUB/354, 291 (1974).

22. R.A. Scriven, 'Physical Behaviour of Radioactive Contaminants in the Atmosphere', IAEA, Vienna STI/PUB/354, 511 (1974).

23. F.B. Smith, 'A Scheme for Estimating the Vertical Dispersion of a Plume from a Source near Ground Level', Unpublished Met. Office Note (1974).

24. L.T. Ritchie, W.D. Brown and J.R. Wayland, 'Effects of Rainstorms and Run-off on Consequences of Atmospheric Releases from Nuclear Reactor Accidents', Nuclear Safety, 19, (2), 220-238 (1978).

25. R.F. Griffiths, 'Effect of Duration of Release on the Dispersion of Effluent Released to the Atmosphere', UKAEA Report SRD R85 (1977).

26. A.J. Russo, 'Reactor Accident Plume Rise Calculations', Sandia Laboratory Report SAND76-0340 (1976).

27. G.A. Briggs, 'Plume Rise Predictions' USDOC, National Oceanic and Atmospheric Administration, Air Resources, Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, ATDL Contribution File No. 75/15 (1975).

28. G.D. Kaiser, 'Radioactive Plumes', Paper 60, IVth Int. Cong. of IRPA, Paris, April 1977.

29. G.D. Kaiser, 'A Description of the Mathematical and Physical Models incorporated in TIRION 2. UKAEA Report SRD R63, October, 1976, and L.S. Fryer 'A Guide to TIRION 4 UKAEA Report SRD R120 (1978).

30. R.H. Clarke, 'The WEERIE Program for Assessing the Radiological Consequences of Airborne Effluents from Nuclear Installations' Health Physics 25 p. 267.

31. G.H. Kinchin, 'Assessment of Hazards in Engineering Work', Proc. Inst. Civil Eng., Part I, 64, (Aug) 431-438 (1978).

32. S. Nair, 'A Reactor Inventory Code for Calculating Actinide and Fission Product Arisings using a Point Source Model' CEGB Berkeley Nuclear Labs. Report RD/B/N4138, October (1977).

33. G.N. Kelly *et al*, 'An Estimate of the Radiological Consequences of Notional Accidental Releases of Radioactivity from a Fast Breeder Reactor', NRPB Report NRPB-R53, August 1977.

34. R.R. Matthews, 'Nuclear Power and the Environment' International Symposium on Man and his Environment, 19th September 1975, Birmingham University, England.

35. J.R. Beattie, J.B. Lewis and R. Lind, 'Graphite Oxidation and Reactor Safety' Paper 185 Vol. 13, page 138. Proc. 3rd Int. Conf. Peaceful Uses At. Energy, Geneva 1964.

36. H.F. Macdonald *et al*, 'Development and Current Status of Emergency Monitoring Procedures at CEGB Nuclear Power Stations', J. Br. Nucl. Energy Soc. 16(2), 177-186, April 1977.

37. C.G. Weir, 'Chapelcross Melt-out and Recovery Operations' Paper 3 Inst. Mech. Eng/BNES Discussion on Active Working on Reactors, London 1970.

38. A. Knockaert *et al*, 'St Laurent-des-Eaux Reactor 1 Fuel Melt-down Accident October 1969'. Paper 4, Ibid.

39. H.C. Orchard and C.W. Walker, 'Experience in the Provision and Exercising of Emergency Arrangements at CEGB Nuclear Power Stations' IAEA SM 215/30, Symposium on the Handling of Radiation Accidents, Vienna, Feb 1977.

40. 'The Generic Safety Issues of Pressurised Water Reactors', Atom, 251, 218, Sept. 1977.

41. W.D. Rowe, 'An Anatomy of Risk', J. Wiley and Sons Inc., New York 1977.

42. D.R. Grist, 'Individual Risk — a compilation of recent British data' UKAEA Report SRD R125, 1978.

43. R.F. Griffiths and L.S. Fryer, 'The Incidence of multiple fatality accidents in the UK' UKAEA Report SRD R110, 1978.

THE ECONOMICS OF NUCLEAR POWER

Nuclear power stations throughout the world are now providing consumers with substantially the cheapest electricity, except in areas with extensive hydro-power or cheap, clean, local coal. Thermal nuclear power stations will continue to provide economic electricity until the cost of uranium rises to several times the present level; fast reactors have the potential to continue to stabilise the cost of electricity and by moderating demand for other fuels will keep down their cost also. These are conclusions to the study presented here, by Hugh Hunt and Gerry Betteridge*

The historical perspective

Looking back over a hundred years we see a close relationship between useful energy consumption and standards of living. This is not surprising, since it is largely external energy that has enabled man to produce much more during his limited life-span than he could unaided, and rescued him from a short and brutish existence. However, it is not only by using more energy that living standards have been improved but also by progressively using sources of energy which require less resources (particularly of labour) for their extraction, transport and processing. Thus, as illustrated in Figure 1 relating to the USA, wood gave way to coal, and coal to oil and gas.

In the world as a whole (excluding the Centrally Planned Economies) between 1945 and 1974, the proportion of energy (measured in terms of primary fuel input) provided by oil fuels increased from 25 to 54 per cent, and that of natural gas from 10 to 18 per cent. During the same period the share of solid fuels fell from 60 to 19 per cent. This means that in a period when overall energy demand has been growing at about 5 per cent p.a., both oil and gas have been rising by 8 per cent p.a.[1]

In this progression, each succeeding fuel has had a higher energy content per unit weight than its predecessor (Table 1). Moreover, liquid and gaseous fossil fuels have largely superseded solid fuels because they are also more easily extracted and transported in bulk and are more efficient in end use. Natural gas is perhaps the ultimate fuel for many purposes in being conveyed from source to consumer with little intermediate handling or processing, and if it was in unlimited supply the story could end here.

Uranium is the latest addition to this sequence. If fully fissioned, natural uranium has a specific energy content some 3·5 million times that of coal. However, uranium ore, as mined, typically contains only about 0·1 per cent uranium. Also, in practice, not more than about 1·0 per cent of the potential energy in natural uranium can be extracted using a moderated (so-called 'thermal neutron' or simply 'thermal') reactor, although up to 60 per cent using unmoderated ('fast neutron' or simply 'fast') reactor. After making allowance for this we get the scale of specific energies for the various fuels per ton of useful material extracted shown in Table 1.

The step-change from fossil to nuclear fuel is such as is rarely encountered in the evolution of a technology. Although nuclear fuel requires much more processing than other fuels before it is in a usable form, its higher energy content more than offsets this. It can be economically concentrated to an almost pure form near the point of mining, so saving considerably on subsequent transport and storage costs compared with fossil fuels.

Energy costs generally have been further reduced by improving the efficiency of appliances in which fuels are consumed[2], e.g.

(a) by moving from reciprocating steam engines to steam turbines in electricity generation; to internal combustion engines for road transport; and to gas turbines for air transport where power to weight ratio is important.

(b) by increasing the size of generating units: (e.g. in the UK from 1 MW in 1900 to 660 MW by 1974. In the USA, 1000 MW generating sets are in use). This, as well as other interdependent technical factors, has played a big part in reducing unit capital costs and in improving the best attainable thermal efficiency from 20 per cent in 1948 to 35-40 per cent today. Average thermal efficiency in the UK system has increased from 8 per cent in 1900 to about 31 per cent today and will increase towards 40 per cent as new plant takes over (Fig. 2).

(c) The introduction of the distribution grid has reduced the overall generating capacity required to provide a reliable service by a factor of 2 compared with what would be required if separate individual local power stations were used[3]. Increasing the grid voltage has also greatly reduced distribution costs. The combined result of these improvements is that today some 137 power stations in England and Wales produce almost 40 times as much electricity as 438 stations in 1925.

Table 1

	Specific energy content therms per ton
Wood	160-180
Coal	230-300
Oil	420-440
Gas	500
Uranium ore refined and fissioned to 0·6-1 per cent in a thermal reactor	4 800-8 000
Uranium ore refined and fissioned to 60 per cent in a fast reactor	480 000

*Economics and Programmes Branch, UKAEA

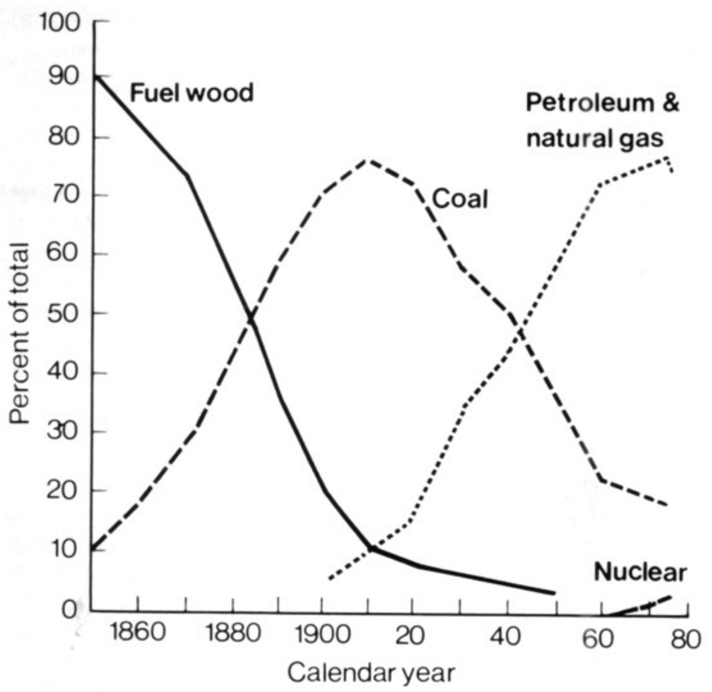


Fig. 1

Source: Historical Statistics of the United States Bureau of the Census; US Bureau of Mines, 1974.

It is by such means as these that, until 1973, the cost of energy has been reduced in real terms despite the considerable increase in the cost of inputs to the energy industries.

Although the price of electricity is several times that of other fuels in terms of simple heat output, it can command this price on the open market in competition with other fuels because it is a high grade energy source of great versatility, cleanliness, convenience and efficiency in end-use. Clearly, these virtues are highly valued by consumers. Moreover, it makes use of low-grade fuels (power station coal, residual oil and uranium) which have at present little other use and could not be burnt as efficiently, if at all, locally. For some applications electricity is the only practicable form of energy.

The five-fold increase in oil prices in 1973, although not completely passed on to consumers, gave us a foretaste of the effect of increasing energy costs. It brought about sudden pressures for change in economic relativities and accustomed life-styles in oil-consuming countries. Although resisted, these pressures persist and their repercussions are a major cause of current world depression and unemployment. A continuation of rising fossil fuel prices due to the increased cost of exploiting more expensive sources will have a more gradually debilitating but more permanent effect.

In these circumstances conservation measures, to the extent that they are economic, will become more important, but cannot by themselves meet the needs of an expanding world population. The need remains for a large new economic source of energy. Uranium with its much higher energy content and no other large-scale uses is the front runner, particularly when used in fast reactors.

Methods of comparing nuclear and fossil generating costs

In electricity production it is especially complex to allocate costs between one type of station and another in a strictly comparable and consistent manner, since within a large system stations are operated in merit order of variable operating cost to meet a continually fluctuating demand.

The economics of any particular design of power station can be looked at in terms of

(a) its own generating cost in comparison with an alternative design used for the same purpose;

(b) the effect of one station on the total generating cost of the whole system in which it has been, or is assumed to be, used;

(c) the effect of a series of stations of one type on the total system cost.

Where load-factors on alternative types of station are not very different, a direct comparison at the same load factor can be made. A more complex method involving analysis of total system cost is necessary if the two stations to be compared will operate at different average load factors over their lives and will affect differently other stations operating in the system. A third even more complex method of systems analysis is needed to calculate the long-term mix of stations which will produce minimum total system generating costs over a period of decades.

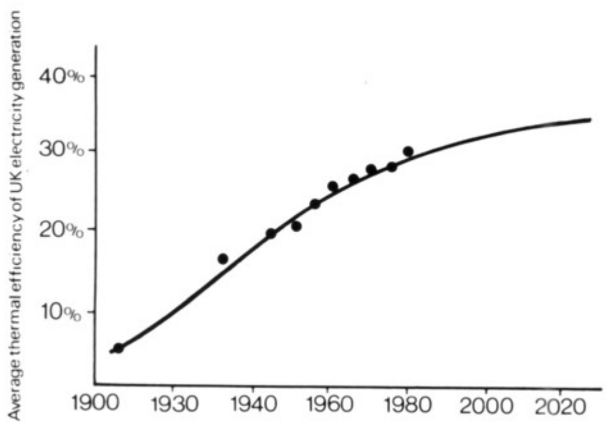


Fig. 2 The average thermal efficiency of generating electricity in the UK. From 1960 excluding nuclear stations. (Source: UK Energy Statistics).

Historical comparisons of UK nuclear and fossil generating costs

The development of nuclear power first assumed importance in the early post-war period when coal output was inadequate. The Suez crisis of 1956 added urgency to the task of finding an alternative fuel, but when, with expanding cheap Middle East supplies and an oil import ban by the US, oil became plentiful outside the US, nuclear power seemed less necessary. The subsequent rapidly expanding oil imports of the USA, Japan and Europe changed all that. In the wake of the oil crisis of 1973 the foresight of the nuclear pioneers became apparent, and it is fortunate that in the UK, the original long-term goal of developing nuclear power as a cheaper substitute for imported oil and deep-mined coal was not abandoned simply because, for a while, oil became the cheapest fuel.

The effect on generating costs of the changing relativities between the costs of alternative fuels is illustrated by the following comparisons[4] of historic generating costs of CEGB nuclear and fossil stations. To increase comparability the comparison is limited each year to stations built during the preceding 12 years. Nevertheless differences in availability of individual stations can affect the comparisons.

Table 2

	Generating cost (p/kWh) of stations constructed during previous 12 years (in current money terms)		
	Nuclear	Coal	Oil
1971/2	0.43	0.43	0.39
1972/3	0.48	0.49	0.40
1973/4	0.52	0.53	0.55
1974/5	0.48	0.74	0.88
1975/6	0.67	0.97	1.09
1976/7	0.69	1.07	1.27
1977/8 (provisional)	0.76	1.23	1.42

N.B. Transmission and distribution costs more than double the cost of electricity to final consumers.

The breakdown between fuel costs, other operating costs, and capital charges of nuclear, coal and oil-fired stations, again up to 12 years old, for the three years 74/5, 75/6 and 76/7 is as shown in Table 3.[5]

The figures for the last few years are not comparable year to year, since the figures for 1974/5 are confined to current costs, while those for later years allow for commitments which will fall to be met in future years. In general, UK generating boards use an 'absorption cost' system, i.e. costs actually borne during the year have been spread over electricity generated during the year. Depreciation has been charged on the cost of construction of the station in equal increments over the life of each station, but interest at the Boards' average borrowing rate for each year is charged on the residual value of the station, which has generally resulted in a falling interest charge year by year. For example, with a life of 25 years and an interest rate of 10 per cent p.a., annual capital charges (depreciation plus interest) fall from 14 per cent to 4 per cent of initial capital cost over the life of the station. Utilities in some other countries, notably the USA, use an annuity or building society amortisation method. This results in a constant capital charge (11 per cent p.a. for the example given above) containing a rising proportion of capital and a falling proportion of interest. Over the life of the station the results are the same, but the UK method gives higher generating costs at the beginning and lower at the end, and direct comparability in any given year is then not possible, at least without correction.

These historic comparisons of UK generating costs are based on standard accounting conventions used generally throughout industry. Such accounting conventions are an entirely adequate way of presenting the actual current costs to utilities and to electricity consumers. Ordinarily the interest rates include an element reflecting the current rate of inflation. In times of rapid inflation this element may not be large enough and this then gives a temporary advantage to borrowers (i.e. utilities). Conversely, in a period of falling inflation, fixed interest rates may over-compensate investors. In the long-term, however, utility average borrowing rates are a reasonable reflection of the market value of money and are the reward necessary to persuade lenders to forgo present consumption. The adoption of Current or Replacement Cost Accounting (in one form or another) is now proposed, to ensure adequate accumulation of funds for replacement of capital assets, stocks, etc. As recently adopted by the generating boards (in the form of a 40 per cent increase in depreciation provisions), Replacement Cost Accounting has apparently narrowed (but not eliminated) the gap between historic costs of nuclear and fossil stations (because of the higher capital cost of nuclear stations) simply by charging current consumers more and future consumers less.

On the basis of actual costs borne by the generating boards, nuclear stations were in 1971/72, generating at the same cost as those burning UK coal. Using cheap (but taxed) oil, generating costs of oil stations were at that time 20 per cent lower than either coal or nuclear stations. Today, with the rise in fossil fuel costs to nearer replacement cost levels, nuclear generating costs are some 38 per cent below those of coal stations, and 46 per cent below those of oil stations.

Those (mainly Magnox) nuclear power stations already operating in the UK, although only 9 per cent of total installed capacity, are generating about 14 per cent of electricity produced and, in comparison with fossil-fuelled stations built over the same period, are currently reducing oil imports by some £250m per annum, of which £100m is a saving to the electricity consumer. When the remaining AGR* nuclear stations now under construction are operating, the nuclear proportion of total output will rise to 20 per cent (from 14 per cent of total capacity). It has been estimated[6] that each AGR station will, when fully commissioned, reduce the generating boards' overall costs by £1½m a week. This will add savings of £375m a year to the savings from existing Magnox stations. Had these additional stations been available sooner, the total savings would of course have been greater, but it is impossble to know the extent to which this could have been achieved using any generating system novel to the UK. Mistakes in the execution of the AGR programme are now self-evident, but this should not be allowed to detract from their competitivity when completed. The high additional cost of providing substitute power at the moment results from the high operating cost of mid-merit fossil plant in current use. As the proportion of nuclear capacity increases, this cost will fall.

It is not only in the UK, that nuclear power is decisively competitive with fossil stations. Utilities throughout the world have testified to the large reductions in consumers' electricity bills

*AGR — Advanced Gas-Cooled Reactor.

Table 3
p/kWh

	1974/5			*1975/6*			*1976/7*		
	Nuclear	Coal	Oil	Nuclear	Coal	Oil	Nuclear	Coal	Oil
Fuel costs	0.13	0.55	0.71	0.25	0.75	0.87	0.34	0.86	1.05
Other operating costs	0.09	0.07	0.05	0.14	0.08	0.07	0.11	0.09	0.08
Capital charges	0.26	0.12	0.12	0.28	0.14	0.15	0.24	0.12	0.14
	0.48	0.74	0.88	0.67	0.97	1.09	0.69	1.07	1.27

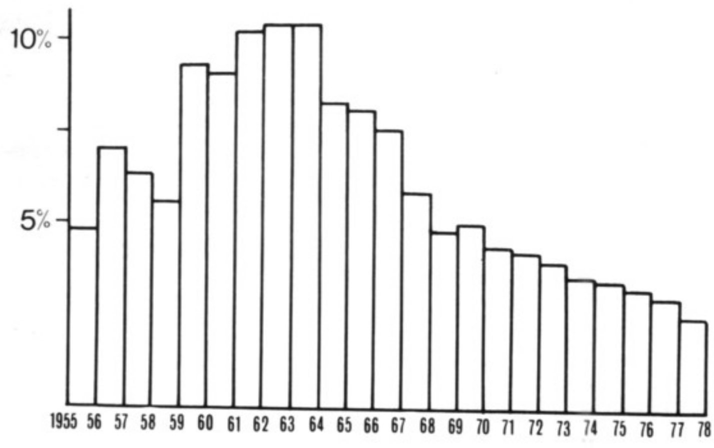


Fig 3. Net UKAEA expenditure on nuclear R & D as a percentage of value of Great Britain electricity sales 1955-1978.

(Sources: Generating Boards and UKAEA Annual Reports).

which have already been made possible by the use of nuclear stations. For instance, in a survey[7] of US generating costs in 1977, the US Department of Energy recorded average generating costs of nuclear stations as being 15 per cent lower than those of coal-fired stations. Allowing for different coal costs in the USA, this figure is comparable with those for the UK.

The gas-cooled reactors now operated by BNFL benefited from the original small fuel fabrication and reprocessing plants built for military purposes. However, Magnox stations operated by the generating boards have borne their appropriate share of the cost of modernising and adding to these plants, and this cost is charged to current nuclear generating costs. The electricity consumer has therefore benefited to a small extent. But nuclear power is not unique in this respect. Many other civil technologies have been launched on the results of military research. Coal-fired power stations benefit from the huge capital write-offs allowed to the coal industry; from subsidies for burning high-cost coal in Scotland and Wales; and for stockpiling surplus output.

The generating cost comparisons just made include current R & D expenditure of the generating boards and (in the cost of nuclear fuel) the current expenditure of British Nuclear Fuels Ltd. on R & D, and on waste storage and reprocessing. They do not, however, include costs being borne by the Exchequer for national reasons, such as AEA research into atomic energy. As in other countries, such research is carried out as part of national energy strategy, to provide the nation with additional energy sources.

Although it is difficult to attribute particular results of R & D to particular expenditure in view of the inter-dependence of technologies, the annual reports of the UKAEA contain a broad allocation of R & D expenditure to major reactor systems. The total cost of all energy R & D ought, logically, to be compared with the revenue of all the energy industries. However, at a lower level some perspective on the scale of nuclear power R & D can be obtained by comparing its cost with electricity revenue, as in Figure 3 covering the period 1955-1978.

This shows that the cost of the Authority's nuclear R & D (including underlying basic research) rose to just about 10 per cent of electricity revenue for a brief period 1961-3 and has since declined steadily to the current level of 2·5 per cent (£116m on AEA R & D against £4822m in electricity sales). This is a measure of the extra cost to electricity consumers if they had to pay directly for AEA nuclear R & D. In total this is of course much more than has been spent on developing any other new energy source. But this scale of expenditure is justified because it is matched by the enormous quantity of additional energy made available by exploiting nuclear technology, and the consequent large potential savings in generating costs.

Waste storage and decommissioning

Also now included in nuclear generating costs are the future cost of waste storage and decommissioning. In 1977-78 the CEGB's provision for such costs was 0·06p/kWh generated by nuclear stations. This is much less than the margin of advantage of nuclear over fossil fuels.

Future changes in costs

It cannot be expected that the margins in generating costs between thermal nuclear and fossil-fired stations will remain unchanged. Indeed, it is an economic truism that in a free market the prices of perfect substitutes will tend eventually to converge. In this case the presence of nuclear power will moderate the prices of fossil fuels, particularly those suitable only for electricity generation, and any assessment of the benefits of nuclear power should allow for this.

So far as capital costs are concerned, the past few years are little guide to what may be expected in future. During the recent period of rapid inflation the cost of all large capital projects increased much more rapidly than prices generally. This was mainly because attempts to simultaneously accelerate expansion of several major world economies resulted in an exceptional increase in commodity prices. However, studies of capital costs over a long period show that they increase at about 1 per cent p.a. above the general rate of increase in prices partly because of their high labour content, and such an allowance is currently made in forecasts of generating station capital costs.

Increases in nuclear fuel fabrication, reprocessing and waste treatment costs will occur, to accommodate the cost of new plants. However, these factors at present account for about 15 per cent of total costs, and the increase in costs would have to be very large to affect generating costs decisively.

As for fuel costs, power station coal prices in the UK now average about £25 per ton. A 20 per cent increase in coal price to £30 a ton by 1985 (in 1978 money) does not appear unlikely in view of greatly-increased levels of investment and the trend in wages.

Uranium bought under existing contracts costs about $20/lb. New contracts for uranium are being let at around $40/lb, so that by 1985 this may represent (in 1978 money) the cost of most supplies. The price of uranium, too, will continue to rise. Lower grade, less accessible deposits will have to be exploited, and there may be difficulty in expanding production by a factor of 10 by the end of the century to match the desired rate of world growth in nuclear power capacity. Unless major deposits are discovered elsewhere, this appears to mean that Europe and Japan will be heavily dependent on N. America, Australia and Africa for a share of limited low-cost uranium supplies. All this implies an increasing cost of uranium and uncertainties of supply. Although this factor is at present a much smaller proportion of nuclear generating cost than that represented by the fuel cost of a fossil-fired station, there will be an increasing incentive to take advantage of the large reduction in uranium requirements possible through the use of fast reactors. It is for this reason that it is important for the development of fast reactor technology to proceed to the point where the UK has a practicable option to use fast reactors.

Criteria for future investment in nuclear power

It is clear that historic costs give no direct guide to future investment, although they do provide a base from which updated estimates can be made.*

The overall criterion is total generating costs. To obtain these for the future, a method is required for adding capitalised costs (of construction including interest and initial fuel) to running costs (mainly of fuel) which occur over the life of the station. This can be done either by calculating the 'annual capital charges' arising from the construction cost, on a conventional accounting basis in terms of depreciation and interest, or amortisation, and adding them to the annual costs; or alternatively by converting the life-time fuel costs into a 'present worth' using a discount rate. A recent Government White Paper[8] recommended the use of 5 per cent (net of inflation) as the rate for use in future to compare alternative investments in the nationalised industries. Using this rate, the 'present-worth' life-time total generating costs due to both capital and operating costs of new nuclear and fossil stations can be calculated, for any given load factor.

The latest estimates of the cost of constructing nuclear stations in the UK (for commissioning in 1985) and their likely fuel costs are contained in the report of the National Nuclear Corporation submitted to and published by the Secretary of State for Energy[9].

Combining these NNC estimates and a CEGB estimate of coal station capital costs[10] gives a basis for deriving a comparison of the generating costs of a new nuclear (AGR) and new coal station.

Differences between the nuclear generating costs quoted above and those given by NNC are accounted for mainly by the use of the new lower 5 per cent p.a. recommended discount rate instead of the previous public sector discount rate of 10 per cent p.a. used by NNC. The above figures are also not comparable with the historic costs given earlier because they are computed using a constant capital charge method and higher real fuel cost assumptions.

Table 4 presents the situation of both a nuclear and a coal-fired station operating at a 70 per cent base-load factor over the whole of its life. Figure 4 then shows total generating cost over a range of load factors, and the effect of higher capital costs and higher real fuel costs over the life of the stations. In the latter case, the load factor represented is the discounted average life-time load factor. (N.B. The effect of rising uranium costs on nuclear generating costs is reduced — and at low load factors is more than offset — by the discounted credit for the final fuel charge). By far the most influential cost in the comparison is that of coal; the second being the capital cost of the nuclear station.

These comparisons show that on the stated assumptions nuclear stations based on AGRs would, when operating at a 70 per cent load-factor, generate electricity some 30 per cent cheaper than coal-fired power stations, and that this cost advantage would not be eliminated until the load factor was only about 40 per cent.

To minimise total system generating costs, the UK generating system is operated on a merit-order basis in which the stations with lowest operating costs are operated in preference to those with higher operating costs. The expected pattern (for CEGB only) in 1982 is shown in Fig. 5.

*A potential source of confusion in comparing estimates is the treatment of inflation. The UK practice is to quote costs in constant money values related to one stated date with no allowance for inflation, but making allowance over the life-time of the station for any real changes in particular elements of costs, compared with the general inflation rate.

Some other countries (notably the USA) make an allowance for expected inflation and quote costs in current money terms for each year.

Both methods yield valid comparisons, from which the same conclusions would be drawn, but direct comparison between estimates on the one basis with those on the other are not valid without correction for inflation.

Table 4

£/kW present worth at 70 per cent load factor (1/1/77 prices)

	AGR		COAL	
Construction cost	470		290	
Interest during construction	70		44	
Total station cost	540		334	
Initial fuel or working stock	68		7	
Final fuel	4		—	
Fixed operating costs	76		55	
Total fixed cost		688		396
Replacement fuel	361		1183	
Variable operating costs	38		27	
Total running cost		399		1210
Generating cost £/kW (rounded)		1100		1600
Generating cost p/kWh		1.23		1.70

N.B. Other assumptions as stated on Fig. 4

From this has been derived Fig. 6 which shows the relationship between load factor, proportion of generating capacity and proportion of electricity generated. 'Base-load' stations operating at 70 per cent load factor will then comprise some 50 per cent of total capacity and generate about two-thirds of total output. Stations operating down to 40 per cent load factor will comprise 70 per cent of total capacity and generate 90 per cent of total output.

Nuclear stations operating or under construction in the UK comprise about 14 per cent of the total capacity expected in 1981; they will have an output of 10 GW(e); and they are expected on completion to generate about 20 per cent of total output at that time. The proportion of nuclear capacity

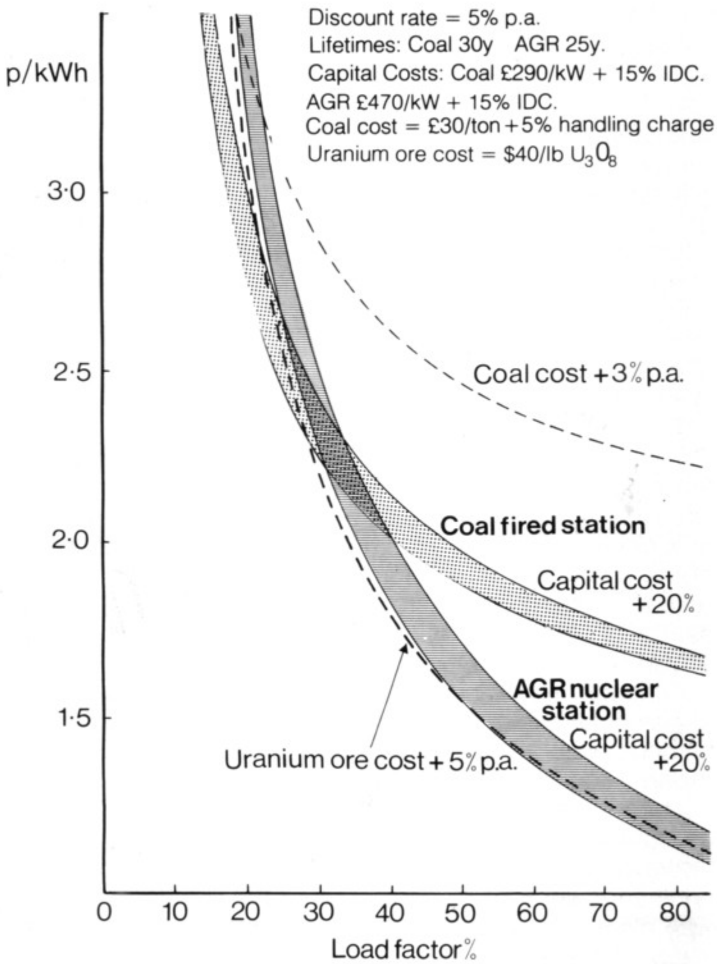


Fig. 4 Comparative generating costs for coal and nuclear stations in 1985.

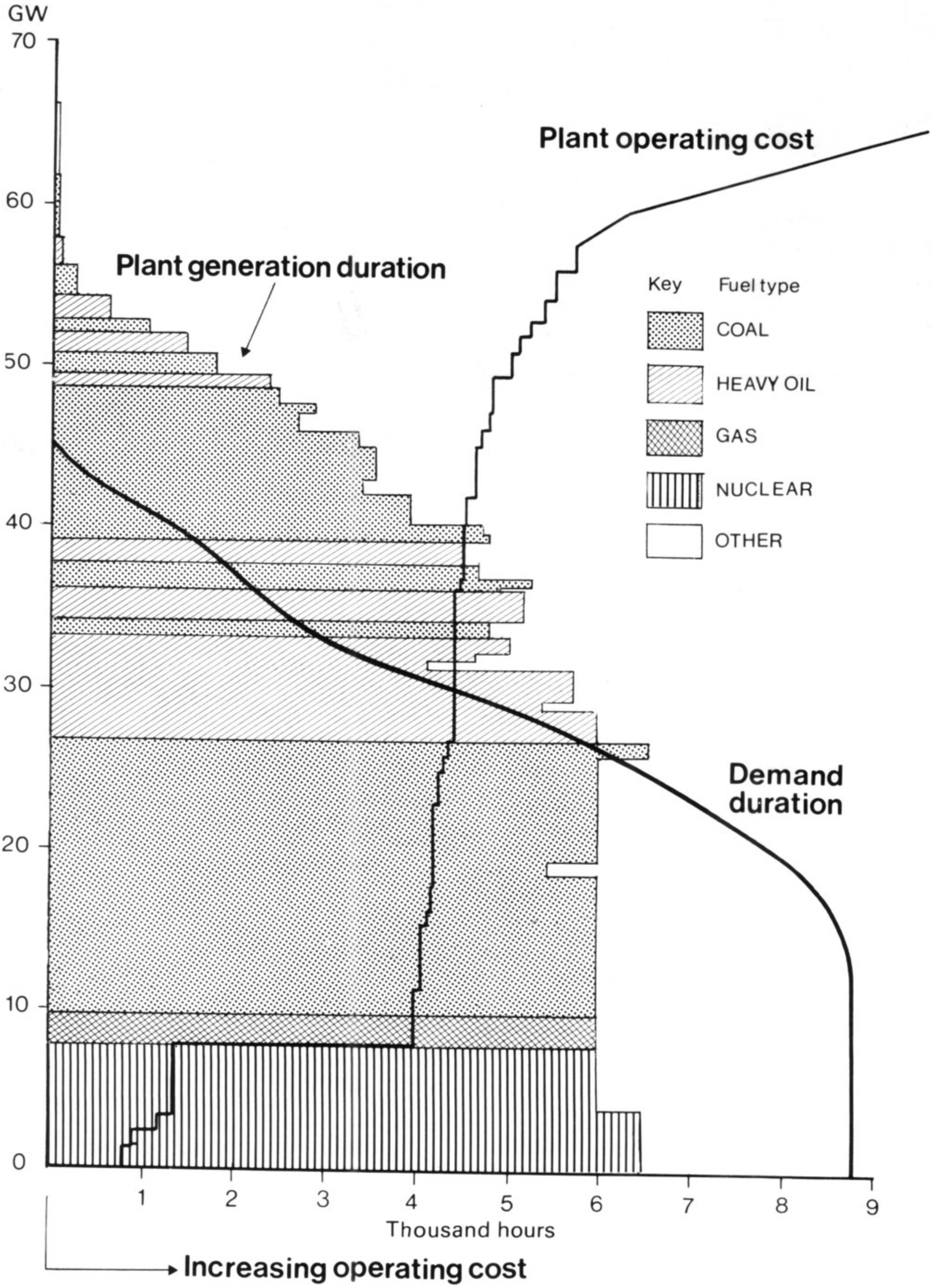


Fig. 5 Estimated mean system characteristics in 1982/83
(Source: S. Catchpole (CEGB), IAEA Salzburg Conference, May, 1977).

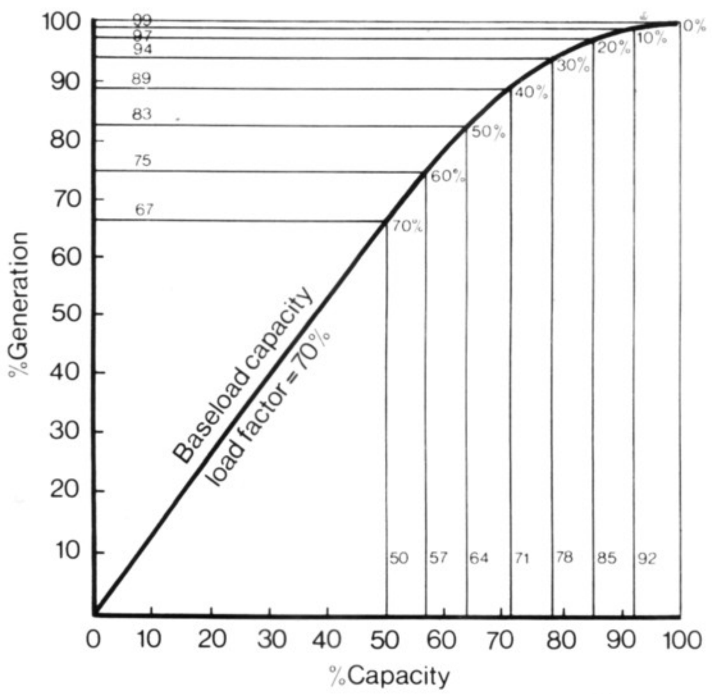


Fig. 6 Annual electricity generation from CEGB power plant.

could be increased by a factor of 4 before all base-load output was from nuclear stations, and by a factor of 7 before the break-even load factor was reached and minimum system generating cost achieved. At this point the generating costs of the dearest nuclear station would equal those of the cheapest coal station (oil stations being assumed by then to be more expensive than either). Optimisation of the system would in practice be unlikely to be taken quite this far, so as to preserve adequate diversity between fuels and flexibility to cater for unforeseeable changes in relative costs.

Alternative methods of comparison

Marginal analysis

The comparison between nuclear and coal stations can be investigated in a number of other ways. For instance, usng the same basic cost estimates, both the Department of Energy[10] and the CEGB[11] have evaluated the marginal difference in life-time system costs between using one nuclear station or one coal-fired station as the next station in a system expanding by the addition of a predominantly nuclear 'mix'. This is the so-called Standardised System Cost method, described in these and other references. The results can be expressed in various ways as shown in Table 5.

Table 5

Index of comparison	System cost advantage of a nuclear station[2] over a coal station
Net effective cost[1]	£50/kW p.a.
Difference in economic worth on a 2 GW station	£100m. p.a.
Return on extra capital cost of a nuclear station	>20% p.a.
Payback time on extra capital cost	4 years

[1]The 'present worth' extra system cost expressed as an annuity per kW of capacity — see Ref. 11.

[2]In this case a PWR.

Source, Reference[12]

The sensitivity analyses included in these studies again emphasise the dominant influence of coal costs. On the nuclear side, capital costs and availability are important, but less influential on total generating costs than coal costs.

It is evident from this that the return on the extra capital cost of nuclear stations is higher than for much other investment in the public sector and justifies preference for this form of energy investment.

All the comparisons so far have been in terms of discounted life-time costs. However the electricity consumer will be more interested to know something about cash flows. For a generating station of 1000 MW electrical output these are:-

Extra capital investment in nuclear station (including interest during construction and initial fuel)	£270m total over 7-8 years
Annual saving in operating cost.	£50m p.a.
Life-time saving in operating cost.	£1250m over 25 years
Period of pay-back of investment.	5-6 years

N.B. This comparison takes no account of the substantially higher investment required to produce the annual fuel requirements of a coal station compared with a nuclear station.

Total system cost analysis

To investigate the effect of introducing different proportions of nuclear stations (both thermal and fast reactors), the discounted total generating costs of the system for the various mixes has to be calculated (allowing for changes in load factor) and compared. From these comparisons the 'mix' with the minimum system cost can be selected. However, because many assumptions have to be made about relative changes in future capital and fuel costs over a long period, this method often produces a wide range of answers. These are valuable for strategic purposes (e.g. for R & D and long-term generating system planning) rather than tactical purposes (e.g. for deciding what stations to add to the system in the short term). Such exercises, if regularly updated, ensure that tactics and strategy remain broadly compatible.

The economics of fast reactors

Liquid metal-cooled fast reactor power stations will cost more to build than thermal reactor power stations, because of their greater complexity. To offset this, their fuelling cost per unit of output will be lower, despite the higher unit cost of fabricating and reprocessing plutonium-bearing fuel. This is because they avoid the cost of buying and enriching natural uranium and, as a higher fuel burn-up is achieved, a smaller quantity of fuel has to be processed per unit of electricity sent out compared to current thermal reactors.

The break-down of thermal and fast reactor generating costs given in Table 6 shows their approximate sensitivity to changes in each major component.

These figures illustrate the importance of nuclear capital costs, particularly for fast reactors. Because thermal reactors will over their life-time have to bear increasing prices for uranium and enrichment adequate to encourage expansion of supply, fast reactors could cost more than thermal reactors and still be competitive. Early fast reactors are likely to exceed the economic level of capital costs, but further development based on manufacturing and operating experience of commercial-scale reactors should enable construction costs to be brought within the required margin.

A complete economic analysis of the effect of the introduction of fast reactors would have to allow for their effect on

Part of the control room of Hinkley Point B nuclear power station. *Photo courtesy CEGB.*

the world price of uranium ore. A large fast reactor component in the world (or even the prospect of it) with an anticipation of a reduced demand for ore compared with all-thermal systems will help stabilise the price of ore and with it thermal reactor generating costs. With large numbers of thermal reactors still operating at the end of the century, this would create a powerful economic incentive for fast reactors which is not reflected in the comparison between single station generating costs, or even in a study of the generating system of a single country.

The ultimate role of fast reactors

Fast reactors will be introduced into the electricity generating system before they are currently competitive with thermal reactors or fossil-fired stations. Electrical utilities will develop a preference for fast reactors as soon as they perceive a likelihood of high uranium prices during the life-time of stations being ordered. The rate of their introduction will depend on requirements for new generating plant and on plutonium availability. Once introduced their low operating costs will put them naturally at the top of the merit order, meeting the base-load. The proportion of fast reactors which it is eventually economic to employ will then be determined by their capital and operating costs compared with those of thermal reactors, and it is quite possible that the most economic course will be to operate fast and thermal reactors together indefinitely.

Conclusion

Mankind has progressed by using increasingly efficient fuels in increasingly efficient appliances. Uranium is the latest of these fuels used in nuclear power stations. Nuclear power stations are, throughout the world, now providing consumers with substantially the cheapest electricity, except in areas with extensive hydro-power or cheap, clean, local coal. Thermal nuclear power stations will continue to provide economic electricity until the cost of uranium rises to several times the present level. Fast reactors, if fully developed by then, have the potential to continue to stabilise the cost of electricity and, by moderating demand for other fuels, will keep down their cost also.

Acknowledgment

The authors of this article are grateful for helpful comments received during its preparation. Responsibility for the views expressed is, however, theirs alone.

Table 6

Illustrative break-down of thermal and fast reactor generating costs.

	Thermal		Fast	
	(Commissioning date 1998)			
	%		%	
Construction Costs		55		67
Fuel Cycle Costs				
Uranium	13		-	
Enrichment	7		-	
Fuel fabrication and reprocessing	15		22	
(incl. Pu value)		35		22
Other operating costs		10		11
		100		100

Source: Reference 13.

References

1 Shell International Petroleum Co. Ltd., quoted by Dr. N.A. White, Energy World, Nov. 1977.

2 Chris Harlow. 'Innovation and Productivity under Nationalisation'. PEP. 1977.

3 Quoted recently at EEC conference.

4 Replies by Secretary of State for Energy to Parliamentary questions.

5 'Electrical Times', 2-9/6/78

6 G. England, Chairman, CEGB.

7 Nuclear Power Program Information & Data. June 1978, p.34. US Department of Energy.

8 Cmnd. 7131.

9 National Nuclear Corporation report entitled 'The choice of Thermal Reactor Systems', 1977.

10 & 11 Energy Commission Paper No.6.

12 G.F. Hawkes, CEGB, 'How the CEGB assesses competing power projects', Nuclear Engineering International, August 1978.

13 H. Hunt, A.A. Farmer. 'Important factors in fast reactor economics', Nuclear Engineering International, July 1978.

THE NONDESTRUCTIVE TESTING CENTRE

The Nondestructive Testing Centre at Harwell was formally established in Quality and Reliability Year — 1967 – and is now the largest unit in the UK carrying out research, development and applications studies in NDT and quality technology. R.S. Sharpe, manager of the centre, reviews here the UKAEA's experience of one of Harwell's longest running industrial programmes.

The Nondestructive Testing Centre, with its headquarters now in the Materials Physics Division at Harwell, was originally set up in the NDT Section of the former Ceramics Division at Harwell early in 1967. It was one of the earliest ventures into diversification following the passing of the Science and Technology Act in 1965, which formally allowed the Authority to undertake non-nuclear research. The desalination project, centred at Risley, had already been operating in a non-nuclear context (with Harwell involvement) for some time when the first two Harwell-based projects were simultaneously launched — the Ceramics Centre and the Nondestructive Testing Centre.

Records show that the foundation stone of the Centre was laid within Harwell on 22 February 1965 when a paper to an internal management committee, from what was then the nuclear NDT Section, proposed that 'as a definite and unique diversification objective . . . it is appropriate to consider whether Harwell with its rare combination of disciplines, skills and facilities should build on the foundations that have been set up in NDT, and form . . . a national organisation for the benefit of British industry . . . to initiate basic investigations, carry out specific projects on behalf of industry, make objective assessments of inspection equipments, provide instructional and educational facilities and assimilate and make generally available world-wide experience from all types of industry'.

As there was no Harwell precedent, this memorandum was to trigger off almost exactly two years of discussion, proposal writing and planning within Authority committees and Ministry of Technology circles before the official 'Requirement' was sent from Sir Richard Clarke, Permanent Secretary at the Ministry to the London Office of the UKAEA on 27 January 1967. The Requirement read: 'I am instructed to inform you that the Minister of Technology, in accordance with the powers conferred on him by Section 4 of the Science and Technology Act, 1965, and after consultation with the Authority, requires the Authority to undertake in collaboration with interested organisations, including research associations and industry, scientific research on methods and equipment for the non-destructive testing of materials, processes and products. The programme of work undertaken by the Authority in this respect shall be such as from time to time agreed between the Authority and the Ministry of Technology and shall be subject to the normal financial approvals'.

It is certainly not without relevance to the subsequent successful development of the NDT Centre that the setting up of such a national research unit was being proposed and encouraged at the same time by organisations outside Harwell. Indeed as far back as 25 October 1963 a view was expressed, at the AGM of what was then the Society of Nondestructive Examination (subsequently amalgamated into the British Institute for NDT), that 'there should be a national centre for research in NDT'. At a subsequent private meeting of SONDE on 13 March 1964, organised to discuss how SONDE could help in promoting research in NDT, it was strongly urged that encouragement be given to 'the establishment of a national centre for research with close links with industry'. This definite proposal by SONDE was taken to a working party of the British National Committee for NDT later in 1964, which then invited wider comments on the suggestion, particularly from Research Associations. As a result of the favourable comments which were received, the Working Party then invited the BNC to consider the proposal 'that the Harwell NDT laboratory was a suitable nucleus for a Centre of this type and that appropriate representation should therefore be made to the AEA'. This proposal was accepted and a formal letter was then sent by Mr Fordham (the then Chairman of the BNC) to the Rt. Hon. Frank Cousins (the then Minister of Technology) urging Government to take positive action in the matter. The reply to the BNC from the Ministry over the signature of Lord Snow, the Parliamentary Secretary said that 'if the Authority decides that the Harwell NDT Group and facilities can be developed along these lines they will submit proposals to the Ministry and I can assure you that they will be given careful consideration'. In view of the common objective, continuing close rapport then developed between Harwell and the BNC as the details of the proposal were formulated and indeed it was during this dialogue that the suggestion of an Advisory Committee was made 'with the majority of its members being connected with industry'. Such an Advisory Committee, reporting to the Director of Harwell, was set up in 1967 and has provided an important link with industrial 'reality' ever since.

So much for the historical record which shows, fairly conclusively, not only that an NDT Centre did fit in with Harwell's initial diversification plans but that it also mirrored strong parallel external opinion that a national research Centre was urgently required to support the empirical NDT technology then being practised. It also, conveniently, but coincidentally, fitted in well with the 'Quality and Reliability' theme that was being injected into industry as a national slogan at that time.

The base of expertise

It is interesting to look back at the fairly strong, but essentially nuclear-biased, technological base on which the Centre's expertise was founded. In 1966 the nuclear NDT Group at Harwell with a staff of seven was involved in:

Ultrasonic micrometry to measure fuel can thickness

Development of a continuous wave ultrasonic 'camera' for fuel plate inspection, based on an ultrasonic sensitive Vidicon converter tube

Evaluation and application of facsimile recording to provide pictorial records of NDT tests

Ultrasonic monitoring of grain size in cast uranium bars

Development of an ultrasonic 'beam plotter' to visualise energy patterns radiating from transducers

Development of panoramic radiography of fuel rings for the Dragon reactor experiment at Winfrith

A slit scanning rig for panoramic radiography of highly-active irradiated rigs

Scintillography with a scanning beam and scintillation counter to develop a new form of radiographic recording of uranium distribution in fuel plates

Techniques of removing scatter to improve radiography of graphite

Assessment of X-ray sensitive Vidicons for television fluoroscopy, and

The use of point-focus radiography for structure studies of reactor materials.

The influence of this early experience has undoubtedly 'rubbed off' as the range and scope of the Centre's work has expanded and can be seen to have been carried over into many of the subsequent programmes as opportunities have presented themselves for wider non-nuclear application of some of these earlier ideas and achievements.

When the Centre was formed there could be little appreciation of how industry would respond in the matter of placing contracts. Starting with an initial spend of around £150 000 a year from Harwell funds, receipts totalled collectively less than £15 000 in the first two years of operation. Fortunately commercial viability was not the prime consideration at that time.

Since then objectives have moved steadily towards higher cost recovery targets and, in addition, the authorising body responsible for the continuation of the Centre's activity has moved from the Ministry of Technology (authorising the spend of Harwell vote funds) to the Mechanical Engineering and Machine Tools Requirements Board (authorising the spend of Department of Industry Research funds). As a result of these changes, coupled with growing industrial interest, the Centre has been encouraged to expand within the framework of Harwell staff resources until in 1978-79 its income, from sources other than MEMTRB, was £1.3 million representing a recovery of 76 per cent.

During the early days of the Centre, when specific industrial contracts were less easy to obtain, the opportunity was taken to build up a strong nucleus of 'underlying research' specifically oriented to non-nuclear industrial NDT requirements — in particular, to those areas where research was thought to be most urgently required. Thus within the first year or two of becoming a national centre, programmes were initiated or expanded on: understanding the structural features influencing the mechanical strength of fibre reinforced plastics and the physical properties which can be used to monitor them;

examining the factors contributing to bond strength and trying to improve methods of inspection by monitoring both cohesive and adhesive strength;

studying wave propagation across thin air-filled gaps and interpreting the results in terms of the significance of detecting laminar flaws;

developing test procedures to measure characteristics of ultrasonic transducers;

studying signal processing and data handling methods in attempts to remove the human element from interpretation of test results and to introduce computer handling of NDT data into automated inspection procedures;

applying correlation techniques to ultrasonic test signals to improve flaw assessment;

designing a range of modular NDT equipment using integrated circuits to provide maximum flexibility for research and development work;

studying wave propagation through high scattering materials by using suspended particles in a liquid as a model in which significant variables are controllable;

developing improved methods of detecting and measuring flux leakage at the surface of magnetic materials;

developing techniques of microfocal radiography, X-ray microscopy and the crystallographic study of fibre orientation;

designing and evaluating an ultrasonic goniometer to study variations in surface elastic properties;

developing a technique to monitor variations in surface electropotential as a means of monitoring corrosion resistance; and

examining the sensitivity and application of a liquid flow meter based on the precision measurement of ultrasonic velocity variations.

In addition to these programmes, initiated within the old Ceramics Division (Division Head at the time Dr. J. Williams) and what was then the Electronics and Applied Physics Division, the Centre encouraged interaction with universities by means of EMR contracts. Indeed it set up the first acoustic emission programme in the UK at Imperial College, supported ultrasonic 'camera' research at City University and set up the first academic neutron radiography programmes at Birmingham University, which helped to spawn much of the subsequent worldwide interest and activity in this particular complementary NDT technique.

This broadening of the scope and research content of NDT set a pattern that the Centre has subsequently adhered to. It produced a spate of published papers that helped to add a more scientific dimension to the literature of NDT and also provided a solid base of experience that could then readily be applied to specific industrial problems as they arose, and as they developed into Centre contracts.

As the original Ministry 'requirement' to establish an NDT Centre was Authority oriented, a northern branch of the Centre was soon established at Risley (then REML), which has acted, over the years, as a co-ordinating point for a small amount of industrial work carried out at Risley, Springfields and Winfrith. The demands of nuclear projects at these other establishments however has precluded any major involvement in the Centre's activities which have therefore been contained almost entirely within the matrix management at Harwell. The Centre itself transferred to Materials Physics Division and appropriate support has been derived from a growing number of other Divisions as the Project has expanded. There is of course a close, and indeed growing, synergy between nuclear and non-nuclear NDT requirements so that the present division is now almost entirely one of accountancy and administration rather than scientific technique or degree of inspection sophistication. As NDT expands its frontiers into 'quality technology' and broadens its involvement into 'structural validation' and 'integrity monitoring' not only do nuclear and non-nuclear boundaries become more and more blurred; so also do those of NDT, materials technology and fracture science. This is healthy development since NDT in technological isolation is hardly a viable entity; indeed, in trying to adopt this stance over the years its practitioners have tended to alienate themselves from the interests and involvement of academic centres.

The Centre's policy, accepted and endorsed by MEMTRB, has been to maintain a 'broad-brush' approach to nondestructive testing and for its staff to involve themselves variously in the whole range of industrial NDT from information, through short-term applications and systems design to research and development. The only aspects of the subject in which there has been no specific conscious involvement are education, training and operator certification which are professionally catered for elsewhere. This policy of broad involvement has contributed to the original concept of a 'national centre' and has, in addition, meant that any part of the programme can, within Harwell, be viewed and analysed in the widest possible context.

The operating framework has also been conditioned by legal requirement. The Centre has had to operate strictly within Treasury accountancy rules and to the rigorous requirements of parliamentary accountability; it must be able to demonstrate a policy of non-competitiveness with British industry, and in its dealings with overseas organisations must not jeopardise or embarrass British trade interests. Operating within the Authority's legal charter it cannot set up a manufacturing facility nor can it offer a routine 'service' that is not specifically linked to a research and development activity. Observing contractual propriety also imposes the obvious constraints of ownership of intellectual property, patent rights and confidentiality appropriate to normal business obligations. The 'overheads' of the Centre have included professional assistance in all of these matters although, being one of the first non-nuclear projects at Harwell, precedents have usually had to be set rather than followed as new situations and problems have arisen.

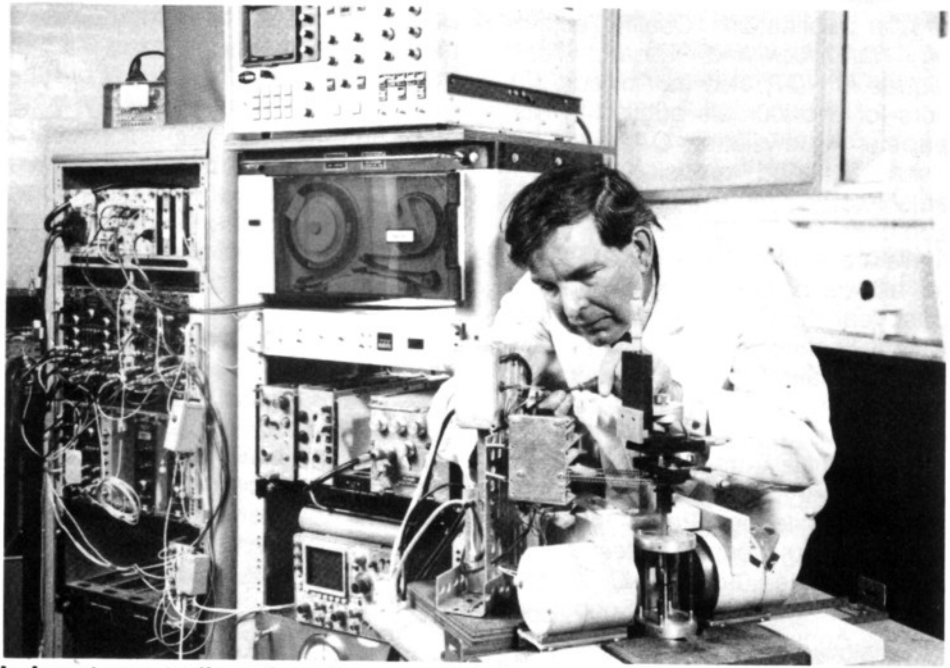
The staff of the Centre have been given encouragement and opportunity to contribute to a great variety of NDT extra-mural activities by committee involvement and conference participation. This close association and commitment with the 'infra-structure' of NDT has undoubtedly enhanced the standing of the Centre whilst, at the same time, enabling its staff to benefit from the closely interwoven national and international network of scientific and technological discussion and camaraderie that has always surrounded the subject. The Centre's operation has also been examined closely by a broad spectrum of overseas contacts and it has undoubtedly provided a pattern on which other national NDT Centres have subsequently developed.

Contract types

An analysis of the contracts placed with the Centre shows that they can be divided into three broad categories. Firstly there are the short-term 'fire-brigade' type contracts from firms who are in trouble with the quality or integrity of their products and require immediate assistance by way of developing or evaluating an inspection procedure outside the scope of their past experience. These (when successful!) often develop into an on-going association with a firm which presents opportunity for more extensive involvement later. Such an involvement with Rolls Royce started as a two-day evaluation of isotope radiography; this subsequently developed into a seven year collaborative programme of dynamic engine radiography which culminated in a joint Queen's Award for Technological Achievement in 1978. Response to such 'fire-brigade' contracts requires staff experienced in the capabilities and limitations of conventional NDT techniques who can identify quickly a method of extending forward from this base of expertise just sufficiently to provide a specific solution to the problem in hand. We have found from experience that the detached deliberation and logical approach of a research scientist can be a distinct encumbrance when dealing with problems of this type.

Secondly, there are 'instrumentation and systems' contracts. These arise when firms faced with a specific inspection requirement, find that available instrumentation has a specification inadequate to match their precise demands. In these situations the Centre, particularly through staff in the Instrumentation and Applied Physics Division, can quickly put together 'tailor-made' systems from a range of Harwell modular NDT circuitry that has been designed and built to meet just such demands. Requests in this category have tended to be particularly concerned with introducing automated inspection procedures, interfacing NDT tests with computers through analogue-to-digital conversion, data processing and data reduction circuitry, or signal processing to obtain a bigger input of variables on which to form quantitative judgements on defect parameters. Apart from electronic instrumentation, the Centre has developed or contributed to the evolvement of a number of other instrument systems. Notable amongst these are a high definition micro-focus X-ray equipment (now licensed to Wardray Ltd.), an infra-red surface coating monitor (now licensed to Anacon Instruments Ltd.), a laser interferometer for surface vibration and displacement monitoring (licence under negotiation), a crack-depth monitoring gauge (now licensed to Unit Inspection Co.) and ultrasonic thickness monitoring gauges (now licensed to Davy Instruments Ltd.).

Thirdly there are 'research and development' contracts. These tend to be forthcoming primarily from other Government Departments or the larger nationalised industries where the requirement to finance anticipated inspection needs is particularly appreciated. Experience has shown that these contracts tend to have a lengthy gestation period and then build up slowly as staged contracts, starting generally with a feasibility study which serves both to test the scientific possibilities and to establish mutual confidence on capability on the one hand and the seriousness of intent on the other hand. Over the years contracts in this category have included automated processing of on-line rail inspection data (British Rail); in-service inspection of natural gas pipelines (British Gas); inspection of fibre-reinforced composite materials (Ministry of Defence); microporosity monitoring in turbine blades (Rolls Royce); processing of satellite data (Department of Environment); crack depth monitoring in welds (Ministry of Defence); acoustic emission monitoring (Ministry of Defence); acoustic holography inspection of rotor forgings (CEGB); dynamic radiography of aero engines (Rolls Royce); inspec-



Laboratory studies of positron annihilation as a possible NDT technique

laser interferometer so that metrology information can be conveniently displayed and corrected for temperature and pressure changes to ensure 1 in 10^6 accuracy. The interferometer design is now being modified in collaboration with a potential licensee to allow it to be used as a vibration monitor with an in-built vibration analysis unit and appropriate display

The laser interferometer has been shown to provide a novel calibration device for ultrasonic transducers by monitoring absolute power dissipation. EEC funding has been obtained to extend this study into a possible European standard

The development and evaluation of capacitative transducers based on metallised foil (termed Polyscan) has been completed. A possible industrial application for such transducers is being evaluated in a separate contract

tion procedures for ILS installations at airports (CAA); property monitoring in as-cast concrete (Department of Environment); and ultrasonic transducer design (Ministry of Defence).

The Centre is also building up an involvement in overseas and multinational research programmes. It has at present an ECSC grant to support work on ultrasonic holography of thick-section welds, an EEC grant to support development of a laser-based ultrasonic transducer calibration system, and a USAF grant on acoustic impact testing, and it is currently seeking support for a joint UK/German programme on internal stress monitoring.

In addition to these three main types of contract, Centre staff, because of their individual specialist knowledge, get called on for consultancy-type contracts by organisations requiring an independent assessment of particular NDT procedures and for critical reviews of specialised areas of the subject. As part of its remit from MEMTRB the Centre also provides an extensive advisory service on inspection procedures to firms faced with particular inspection problems. To assist in providing a speedy and comprehensive service, staff make use of a computerised NDT data store which now comprises nearly 30 000 key-worded articles and papers which is now the most comprehensive world-wide store of NDT literature available anywhere.

Developing new ideas

All of this sponsored contract work derives from the continuing programme of MEMTRB-financed research which allows staff to develop new ideas and evaluate new techniques in properly structured scientific experiments. This MEMTRB programme also allows discussion and publication of results in ways which are generally denied those working on confidential contracts for particular firms or organisations. Brief mention of activity in these research programmes during the past year will serve to give some idea of the present scope and direction of this work.

An ultrasonic diffraction technique for sizing surface-opening cracks has been studied in more theoretical detail, and experimentally on a variety of sample geometries and materials (in particular in thin sections where crack sizing to $\pm$ 0·05mm has been demonstrated, and in austenitic alloys)

Volumetric defect sizing by the use of 'creeping' waves has been demonstrated and signal averaging techniques have been introduced to improve sensitivity. A link to a PDP 11-03 computer has been established for a more complete evaluation of signal averaging capability

Improvements in ultrasonic transducer performance are being sought through designs based on improved ceramic manufacture

Three prototype infra-red thickness monitors have been constructed and two are being evaluated in industry, on paint monitoring and lithographic emulsion monitoring. A licensing agreement has been concluded for exploitation

Microprocessor data handling has been incorporated into the Centre's

Computer routines

A set of computer routines (termed DAISY) for analysing periodic or intermittent acoustic signals has been produced. They are being used in support of research on acoustic emission, impact testing and ultrasonic signal conditioning

A collaborative programme with the Cement and Concrete Association has shown that as the elastic constants of concretes can now be calculated from those of the cement and aggregate components to the same accuracy as densities, the values of ultrasonic velocity and gamma ray attenuation can be calculated for any given composition. This now allows the experimental determination of the composition of concrete samples and gives an indication of concrete quality that is better than can be gained from either measurement singly. A contract to develop this work has been obtained

A technique of computation similar to that used for the case of concrete has been applied to a range of fibre-reinforced composite materials. It has been shown that measurement of appropriate wave velocities would suffice to determine separately the fibre volume fraction and matrix porosity in carbon fibre-reinforced plastics. In the case of glass-reinforced plastics an ultrasonic velocity must be combined with another measurement, such as density

Calculations of the variation of ultrasonic reflected and diffracted signals with angle of incidence of compression waves on a crack have been made by staff in the Theoretical Physics Division. The calculations solve the elastic wave equation numerically using a finite difference scheme which takes into account all mode-conversion at free surfaces including Rayleigh wave propagation

A calculation has been performed on the reflection of ultrasound from a liq. Na-filled slit. A conclusion is that such a slit could be missed in an ultrasonic inspection if the slit were less than 10^{-2}mm thick with respect to a normally incident beam. Experimental confirmation is being made

A working prototype of a film-scanning device using a laser and photo-diode matrix has been assembled for use as a digitiser for automated radiograph interpretation. Preliminary studies have also been made of methods of information processing to detect and interpret significant radiographic detail

Work has continued (with ECSC additional funding) to evaluate shear wave ultrasonic holography of thick section plates. Particular attention has been paid to means of correcting image astigmatism associated with the geometry of the inspection. An electronic reference signal has also been developed which is capable of significantly improving resolution of B-scans (linear holography)

Definite evidence has been obtained that positron annihilation is sensitive to processes occurring in titanium alloys during the early stage of fatigue damage and in particular that it is a sensitive detector of plastic deformation. Small positron sources (Ge 68 and Na 22) which when placed in contact with a surface can be used to probe defect structure on a 1mm spatial scale have been developed. These sources have been used to map the plastic zone around a fatigue crack in ferritic steel

Instrumentation development has centred on the use of microproccessors to control test procedures and to collect, process and interpret test data automatically, particularly in the field of ultrasonics. A number of specific automated systems for on-line quality control have been designed and commissioned during the year.

Attention to national need

One of the original aims of the Centre was 'to provide a national focal point . . . to improve and extend techniques of materials inspection'. A focal point in this context implies a radiating outwards of information and experience in intelligible lay language and this technology transfer responsibility has been a foremost priority objective, particularly as the Centre's programme has expanded and become more complex. Centre staff are responsible for the editorial content of two regular publications, *Quality Technology Handbook* and *Research Techniques in NDT;* also as Advisory Editors for two journals publishing NDT papers. A newsletter, *QT News,* has been launched, arousing considerable interest; more than 400 visitors come to the Centre each year and there are around 500 requests a year for advice or assistance. During the past year the Centre, in collaboration with its licencees, was represented at the Materials Testing Exhibition and papers have been presented at conferences organised by the British Institute of NDT, the Society of Chemical Industry, the UK Mechanical Health Monitoring Group, the Ultrasonics International Conference on Acoustics, the European NDT Conference, EURATOM Summer School and the IIW Annual Symposium. All of this adds up to a serious and effective attempt at meeting yet another of the Centre's original aims which was 'by initiative and example, to direct attention to the national need to extend the application of NDT methods of evaluating material quality in industry'.

So much for the historical record and the account of current activity; what of the future? Computers, microprocessors, digital signal processing, image analysis and pattern recognition are all opening up new opportunities for improving the reliability and reproducibility of NDT tests. These are obviously areas where Harwell can and should make a significant contribution. However developments in these areas necessarily require that much closer attention be paid to the quality and significance of the NDT test signals themselves, which means that transducers and their associated signal processing instrumentation must receive closer scrutiny; there must also be better understanding of the interactive effects between structural features of materials and the probing beam used for interrogation. In parallel with this move to more sophisticated and more automated procedures for both inspection and surveillance there will be a continuing requirement also to produce simple, portable operator-controlled devices for site inspection with proper attention being paid to operator-system interaction.

There is a need also for more emphasis on the quantitative characterisation of defects and, hand-in-hand with this, a closer awareness of the significance of the results of NDT tests in terms of product performance or structural integrity.

The foundations on which the NDT Centre were established, and the experience and confidence built up since in the close involvement with industrial problems, should make it possible not only to back-up future requirements as they present themselves, but also to influence the speed and direction of developments in this rapidly expanding field.

IONISING RADIATIONS

A proposed comprehensive framework of controls on the use of ionising radiations, designed to give greater radiological protection to workers and the general public, is outlined in a consultative document* published by the Health and Safety Commission, which aims to consolidate, harmonise, update and clarify the large and diverse body of statutory requirements, non-statutory codes of practice, and general guidance on radiological protection which currently exists in Britain.

The consultative document proposes that draft regulations be drawn up under the Health and Safety at Work Act to replace the present Ionising Radiations Regulations of 1968 and 1969 — which only apply to factory premises — and the various voluntary codes of practice observed by other users such as in medicine, dentistry, research and teaching. The regulations would lay down standards for the health protection of all workers against the danger of ionising radiations and for the general public in respect of radiation arising from work activities.

The role of regulations, says the consultative document, would be to define objectives, set down procedures where no choice or alternative is possible (such as notification of use, over-exposure or dangerous incident), specify basic permissible levels of exposure, make provisions for record-keeping systems, create a system of recognition of qualified experts and to deal, in a general way, with the provision of suitable plant, facilities and specialised protection and medical services.

They would be in line with a Directive adopted by the Council of Ministers of the European Communities in 1976 under the Euratom Treaty. This treaty

*'Ionising Radiations Regulations: Proposals for Provisions on Radiological Protection,' Consultative Document, HM Stationery Office, price 50p plus postage.

requires that basic standards should be laid down in the Community for the protection of workers and the public against the dangers arising from ionising radiations. Apart from compliance on basic standards of radiological protection, the regulations would comply with the Directive on its requirements for registration of the use of radioactive substances and other activities involving a hazard from ionising radiations.

However, because the European Commission is at present reviewing the Directive in the light of recommendations by the International Commission on Radiological Protection (ICRP) and may propose limited changes, no table of dose limits has been included in the consultative document but it is expected that the annual dose limit will remain at 5 rem per annum for classified workers. A second consultative document will be issued in due course to contain the actual text so far as possible, of the proposed legislative material, including a table of dose limits.

Because of the difficulties of building sufficient flexibility into one set of proposed regulations to satisfy all work situations, the consultative document advocates a multi-tiered approach where, for all work activities, approved codes of practice would be drawn up to give practical guidance on the general requirements of the proposed regulations, supplemented by in-depth guidance notes. Each code of practice, says the document, would be written in a non-legal and understandable way.

The document says that while failure to comply with a code would be *prima facie* evidence of a breach of the regulations, the multi-tiered approach would allow other equally effective methods of achieving basic standards to be accepted, so avoiding unnecessary rigidity in the face, particularly, of advancing knowledge and techniques.

Scope of the proposed ionising radiations regulations

It is proposed, says the consultative document, that the regulations would apply to all work activities in Great Britain, including offshore installations to which the Health and Safety at Work Act has recently been extended. They would apply to all hazards arising from ionising radiations, including those not required to be notified under the proposed regulations.

Among the major areas covered in the outline proposals for the new regulations are:

prior reporting of processing, handling, use and storage of radioactive substances and any other activity which involves a hazard from ionising radiations. Similar notification requirements are suggested for the transport of radioactive substances with certain exceptions. Exemptions would be given for the use of timepieces and navigational instruments containing radioluminescent paint (except when manufactured, repaired or stored in bulk) and for domestic television receivers;

reporting of incidents involving the loss, theft or dispersal of radioactive substances;

a requirement that the exposure of persons to ionising radiations should be kept as low as reasonably practicable and, in no case, to receive a dose in excess of the limits to be specified in a schedule to the proposed regulations;

the designation as 'classified workers' of those liable to receive more than 30 per cent of the annual dose limit at work. These workers would be subject to medical surveillance and to monitoring and recording of doses actually incurred. All excessive doses sustained would be reportable. The document also suggests that radiation dose records for classified workers should be maintained by approved personal dosimetry laboratories instead of by employers. Appendix 6 of the consultative document outlines proposals on dosimetry and record keeping;

the designation of work areas, classified according to the degree of potential for worker radiation exposure;

where operations create a possibility that workers will receive more than ten per cent of the maximum permissible annual dose, employers would be required to appoint and consult qualified Radiation Protection Advisers, while Radiation Protection Supervisors would be appointed locally to give immediate practical supervision, and so extend in-house measurement and control of radiation risks;

a requirement that employers prepare emergency plans for dealing with any reasonably foreseeable situation which might give rise to significant levels of exposure. Employees would be instructed as to arrangements and rehearsals required;

a requirement for the preparation of hazard survey reports for sites other than those licensed under the Nuclear Installations Act of 1965, in which substantial quantities of dispersible radioactive materials or fissile materials are to be processed, manufactured, used or stored.

Approved codes of practice

Appendix 2 of the consultative document outlines in detail proposals for an approved code of practice on 'general matters' designed to assist in complying with the general requirements of the suggested regulations. This code, says the document, would cover general matters in the control of ionising radiations, while matters specific to particular fields of work such as industrial radiography, medical, dental, veterinary or transport, would be dealt with in separate codes.

Detailed proposals for these specific codes of practice are outlined in appendix 4 of the consultative document, while appendix 3 outlines a suggested approved code of practice on hazard survey reports. The document says that, at a later stage, other codes of practice on specific topics might be produced, such as for:

special areas of research (for example tracer use);

special aspects of medical practice (such as nuclear medicine);

power and research reactor use;

nuclear fuel processing and fabrication

Guidance notes

It is unlikely that approved codes of practice could give sufficient detailed advice and guidance on every topic, taking into account local circumstances, to stand on their own, says the consultative document. Many employers may wish to supplement the material with local rules aimed at the supervisor, training officer or worker. "Guidance notes will not have a legal status under the HSW Act but, of course, many employers may wish to incorporate their suggestions in their own work procedures," it says. "The basic intention remains, however, for guidance notes to reflect regulatory requirements, to be educative, to encourage an understanding of the hazards and the adoption of good practices."

Initially, guidance notes will be prepared jointly by the National Radiological Protection Board (NRPB) and the HSE. A synopsis of these proposals is given in appendix 5. Consideration will be given to the possible preparation of additional guidance notes to meet any need which may be identified.

Comments on the consultative document, which is being circulated widely to the CBI, TUC, government departments, local authority associations, nationalised industries, and other interested parties, should be sent to: Mr. R.P. Whitehead, Health and Safety Executive, HSD-E, 25 Chapel Street, London, NW1 5DT.

FUEL—THE BROADER PERSPECTIVE

Future strategy should be based on the assumption that the real cost of energy is likely to rise substantially at some time not far away, Sir John Hill, chairman of the UKAEA, urged at the second National Energy Management Conference in Birmingham in October. He therefore commended a policy of conservation and efficient use of energy.

A new peak

The two-day conference was organised by the Department of Energy. Dr John Cunningham, Parliamentary Under-Secretary of State with responsibility for energy conservation, said the conference's success in attracting more than 800 key men in industry, commerce and the public sector meant that energy management was now "firmly on the industrial and economic map. As a result, thousands of energy-using organisations — factories, offices, schools and hospitals throughout the country — are enjoying lower fuel bills and higher energy efficiency with all that implies for prices and public expenditure". The conference marked a new peak in the continuing growth of energy management as an industrial and commercial tool in the UK.

Dr Cunningham said the Government's direct financial commitment to energy conservation had been boosted from about £15 million a year to more than £100 million from 1979 onward; the amount earmarked for the first four years of the Government's ten-year programme of energy conservation was now more than £450 million.

"The Government's aim is to cut by a fifth the energy we might need in the year 2000," he said. "If necessary, we stand ready to put more financial muscle behind our efforts. This clearly demonstrates the role energy conservation will play as a central pillar in our long-term energy strategy. After all, energy saving is a very profitable way of helping to close any looming 'energy gap'."

An enormous energy glut

Sir John spoke at a dinner attended by delegates at the end of the first day, asking and answering the questions: Is conservation necessary? How much should we spend on conservation, and is it urgent? Would it not be cheaper to produce more fuel?

We have over most of the industrialised world and certainly in this country the paradox of talking about the energy shortage, bemoaning the high cost of oil and discussing conservation measures, all in the middle of an enormous energy glut (he said). Although the situation in this country is in some respects not typical of the rest of the world, what happens in the rest of the world will determine the events in this country and not the other way round. So let us consider first the world scene.

There is no world energy shortage today. The reason is that all the important energy supplying industries have to plan seven or more years ahead because that is the time it takes to develop a new oil or gas resource or build a coal mine or a generating station. Up to 1973 all energy planning was based on continuing rapid growth of energy demand and these are the plans that are coming to fruition now and will continue to come to fruition until about 1980.

The supply side of the energy equation has been based on a growth in demand that has not taken place. The result is tankers laid up, refineries operating at half capacity, a world depression in shipbuilding and coal consumption having to be subsidised to keep stocks to manageable levels.

But what of the future? Will this situation last? Clearly it will not. The energy industries have re-planned their operations to a much lower rate of growth in the industrialised world and today's imbalances will in a few years be rectified. But the underlying reasons for the worries about world energy supplies that were expressed so forcibly a few years ago, and now seem to be forgotten, still remain. The forecasts of rapidly increasing world population have not changed.

Although Europe, Japan and North America have a fairly stable population age distribution — and by this I mean that there are nearly as many people of 60 as there are of 16 — this does not apply to the heavily populated developing world where perhaps half the population is aged 16 or under. With this number of young people a vast increase in world population is inevitable even if from today it were possible to decree that all families must be limited to two children and none of us believes that this is going to happen in the foreseeable future.

Whether or not the wealthy industrialised countries should strive for an even higher standard of living and even whether they should be allowed to continue consuming energy at their current rate is a philosophical argument I do not wish to engage. What is however abundantly clear is that the poor nations desperately want to raise their standard of living not only for their present population but for the much larger population that they will inevitably have in the future. This is going to result in their consuming much greater amounts of energy than they do now.

We have the situation where either the poor countries will get poorer and poorer year by year, or the world must produce much more energy in the future than it does now, or the Western industrialised countries must consume very much less than they do today. The oil industry is clear that it cannot for much longer continue to expand production to meet this demand — we must use what we have more carefully and develop alternative energy sources. This is the inevitable conclusion of any long-term world energy study and was brought out forcefully at the World Energy Conference at Istanbul last year.

The world scene

But what then is happening — something admittedly, but not very much. The American energy situation is tragic. Five years after the energy crisis of 1973, oil and gas are still being sold at substantially below world prices. Half their oil is imported and this has not only damaged the dollar but will result in world oil prices, not only to them but to everybody, rising sooner and faster than they otherwise would. The American nuclear industry — once world leader — is now in total disarray having received more cancellations than orders in the last four years. Steps are, however, being taken to increase coal production to reduce the amount of oil and gas used in the electrical supply industry and measures are being taken to improve petrol consumption in motor cars.

In Japan, Sweden, Italy and Denmark there are virtually no indigeenous fossil fuels and the case for nuclear power is overwhelming. The nuclear programmes are, however, being held up to a greater or lesser extent in all of these countries by various pressure groups. Germany too is energy deficient and would like to have a larger nuclear programme. Only France in the western world is going ahead at full speed with a nuclear programme designed to make their electricity network independent of fossil fuels within about ten years.

In the UK we have an almost unique position of rapidly increasing supplies of oil and gas combined with low economic growth and nearly stagnant total energy demand. Oil is taxed up to world prices and can be consumed at home or sold abroad and therefore contributes greatly to Government revenues and balance of payments, but does not significantly change the energy picture. Gas from the southern basin of the North Sea is a very low cost premium fuel — while it lasts. It is being purchased by the Gas Corporation under 'take or pay' contracts at a fraction of the cost of extracting coal. Unlike oil it is free of all taxes. The oil fields to the north also produce gas which comes out of solution when the pressure of the oil is reduced. It cannot be pumped down the well again and must be consumed or flared. The quantity coming ashore from these fields is therefore determined by the oil production programme, not the gas consumer.

The result is obvious. Gas is taking all the growth in energy demand. It is supplying demands which would otherwise have been met by coal and electricity. The Government is again having to subsidise the burning of coal to keep stocks to reasonable levels. Growth of electricity demand is very slow. Few new generating plants are being ordered, to the detriment of the long-term energy suppliers, nuclear electricity and coal and, of course, the engineering industry that supports them.

Cheap energy

We are in effect pursuing a cheap energy policy in this country — not to anything like the extent of the United States but to the extent of accepting a fairly rapid depletion of our oil and gas reserves and an only slow build up of our alternative long-term energy supplies. The issues that have to be decided are: How much gas, if any, do we propose to leave to the next generation? How much oil, if any, do we propose to leave? How much nuclear capacity do we expect to have when the supplies of cheap oil and gas diminish?

Democracies unfortunately do not give much heed to the future. The real cost of energy is certain to rise substantially at some time not far away and I therefore commend to you a policy of conservation and efficient use of energy. Furthermore it will not be possible to produce instant nuclear power stations or coal mines when the need becomes urgent.

As an example of energy saving, in the nuclear industry we have developed jointly with Germany and Holland an improved method of enriching uranium for nuclear power stations which is very much more efficient than the earlier process. To illustrate the energy consumption of the earlier process, the three huge plants built in the United States consumed a continuous 7 000 000 kW which in the early 1950s was not all that far short of the total annual electricity consumption in England. The new centrifuge process uses less than 10 per cent of the energy to produce the same product and I am sure this energy saving will be decisive.

We should all base our future strategy on the assumption that energy — particularly fossil fuel energy — will become substantially more expensive in real terms. Yes, I commend insulating factories and home. Not, however, as in some parts of Sweden where the ventilation of some houses has been reduced to the extent that radon from the natural radioactivity in the structure of the house is giving perhaps 100 times as much radiation to the occupiers as they would get if they left the windows open and heated the house with nuclear power.

Separation Processes Service

The Harwell Separation Processes Service has enrolled its 25th member company. It is Barr and Murphy Limited, a small London-based company manufacturing driers, who recently won a Queen's Award for Export Achievement.

The project manager of SPS, Dr Philip Hawtin, said: "We regard this as something of a milestone, indicating that a cooperative venture like SPS is of recognisable value to a broad cross-section of industry. The current joining rate of about one company a month strengthens this view".

SPS provides a service to the chemical, process plant, food and allied industries. It provides design information, consultancy and research on selected separation processes, making full use of the resources of Harwell and the Warren Spring Laboratory of the Department of Industry.

Where appropriate, other centres of expertise are also contracted to do work for the service. Earlier this year a £63 000 research contract was placed with the University of Bradford to develop design procedures for column contactors in liquid-liquid extraction. The service has just placed a three years £50 000 research contract with University College, London for work on the scale-up of crystallisers. The work is being supervised by Professor John Mullin and Dr John Garside.

A leaflet giving full details of the design, information, consultancy and research services available, as well as explaining how firms can join SPS, is available from: Dr. Philip Hawtin, Project Manager, SPS, Building 351.28, Harwell, Oxfordshire OX11 ORA. Telephone Abingdon (0235) 24141, extension 4642.

27 September 1978

The need for nuclear power

A leaflet "Energy and the need for nuclear power" is now available from Information Services Branch, UKAEA, 11 Charles II Street, London, SW1.

The author, L.G. Brookes, Senior Economist, UKAEA, outlines in simple terms the likely need for energy over the next few decades, if developed countries are to maintain their living standards and poorer countries improve theirs; describes the contribution possible from coal, oil and 'renewable' sources; and stresses the role that nuclear energy can play in providing cheaper electricity, so reducing prices of all other fuels.

Atom on Film

A new edition of the UKAEA's film catalogue is now available. It lists films and other visual aids available on free loan, covering most aspects of nuclear power research and development, presented in both technical and 'popular' terms.

The catalogue can be obtained on application to: The Film Library, United Kingdom Atomic Energy Authority, 11 Charles II Street, London SW1Y 4QP. Tel: 01 930 5454 Ext. 488.

CRITICAL COMMENT ON THE MANCUSO STUDY

A number of experts have criticised the Mancuso study — the investigation of the effects of low levels of radiation on workers at the Hanford Works, Richland, in Washington State, USA — and the NRPB has published a report* drawing those comments together.

The report summarises the main points from various criticisms, including those made by staff of the US National Cancer Institute and by Dr. B.S. Sanders, formerly Dr. Mancuso's statistician.

In a study of the accumulated doses and causes of death of those employed at Hanford Dr. T. Mancuso and co-authors Dr. Alice Stewart and Mr. G. Kneale claimed to demonstrate a strong association between low levels of exposure to ionising radiation and certain types of cancers.

Since direct information on the human health effects of low levels of radiation is of crucial importance in radiological protection, Dr. J.A. Reissland of the NRPB has collected together the salient points made in various publications.

Dr. C.E. Land, US National Cancer Institute, has noted that an analysis of about 2200 workers with an average cumulative dose of under 2 rads purports to provide statistical evidence of radiation-induced cancers. The mean doses of the various groups of Hanford workers are very low — an "exposed" worker being defined as anybody with greater than 0·01 rads lifetime recorded occupational dose. Since the average dose due to background natural sources of radiation is about 0·1 rads per year, any individual aged 50 years will have accumulated a radiation dose similar to the highest dose range considered, that is 5 rads and above.

Dr. T.W. Anderson, University of Toronto, has pointed out that the confounding effect of background and other non-occupational exposures, such as medical X-rays, casts doubts on any conclusions drawn from analysing exposures small than the random variations in the total radiation doses experienced by the study population.

Dr. Anderson and others have also noted that the study relies on the mean cumulative dose when most of the dose is concentrated in a small number of workers. The effect of this is shown in the following analogy: the mean income of ten families, one with an income of £1 000 000 per year and nine each of £1 000 per year, is £100 900 per year. This average income would not be a good basis to describe their patterns of expenditure. Dr. B.S. Sanders, a statistician who was once employed on the Hanford study, has drawn attention to the fact that radiation doses incurred in subsequent employment after leaving Hanford are not included; in some cases doses incurred prior to working at Hanford will not have been included.

No attempt is made in the study to consider any other carcinogenic agents to which the workers may have been exposed even though almost all exposed workers are involved with other agents, eg, asbestos. Another point made is that the study takes no account of the dominant cause of lung cancer — smoking.

One effect of any study which is basically a proportional mortality study is that a decrease in one cause of death produces an apparent increase in another. Most employed groups exhibit a "healthy worker effect" due to absence of the chronically ill from these groups. This does not influence the patterns of all diseases uniformly; in particular, the diseases of later life such as cancer are less affected by the healthy worker effect. Hence, as Dr. Anderson has pointed out, the proportion of cancer deaths may be expected to be higher than normal in a working group and it would be better to base a proportional study on the number of all cancers rather than on all causes. A good example of the effect of this is that if the expected number of neoplasms of the reticulo-endothelial system is based on the proportion of all-cancers, there is a deficit of 6.8 neoplasms compared with an excess of 11·1 calculated in the Mancuso study.

Dr. Reissland summarises as follows:

(i) There is wide agreement that the Mancuso study does not represent a valid statistical interpretation of the actual data.

(ii) Associations claimed by the authors would largely disappear when the data are properly standardised, although cancer of the pancreas and the bone marrow disease, multiple myeloma, remain with a statistically significant excess.

(iii) There is no justification for the reduced sensitivity between ages 25 and 45 years deduced in the study, neither are any of the calculated doubling doses meaningful.

(iv) Despite the claims of the Mancuso study, a wide body of experts agree that there is no evidence in the Hanford data to support the suggestion that ICRP values seriously underestimate the risk.

Further information is available from the Information Officer, National Radiological Protection Board, Harwell, Didcot, Oxon OX11 ORQ, telephone Rowstock (023-583) 600, Ext. 410.

2 October 1978

*NRPB-R79. An assessment of the Mancuso Study, J.A. Reissland. HMSO £1.00

Safety of Chemicals in the Environment

'Safety of Chemicals in the Environment' is the title of a two-day seminar to be held at Harwell on 9-10 May 1979.

The event is the second in Harwell's series of environmental seminars, the first of which was the highly successful 'Major Chemical Hazards' seminar held at The Lorch Foundation, Lane End, Buckinghamshire in April this year. 'Safety of Chemicals in the Environment' is to be held at the same venue.

The seminar is designed to appeal to all concerned with the safety of chemicals and those having a direct responsibility to protect the environment against both short and long-term toxic and polluting substances.

Its stated aim is: 'To examine the effects of chemicals in the environment with particular emphasis on the issues of control, production, use and disposal.'

The seminar, which is expected to have an international appeal, will cover the following topics: origins of chemicals in the environment; detection and toxicology; effects and epidemiology; regulatory implications in the United Kingdom, Europe and North America; industrial viewpoints; ecological aspects, and future developments.

The full programme, including names of speakers, will be announced in due course.

Further information about the seminar can be obtained from Mr. C.J.A. Preuveneers, Education and Training Centre, Building 455, Harwell, Oxfordshire OX11 OQJ. Telephone Abingdon (0235) 24141, extension 3106.

6 October 1978

INDEX: JANUARY-DECEMBER 1978

O

TITLES OF MAIN ARTICLES

JANUARY
Nuclear power and the public good
Sir Francis Tombs to the British Nuclear Energy Society in London.

The treatment and disposal of liquid waste in the nuclear power industry
Dr. J.B. Lewis to a symposium organised by the University of Newcastle upon Tyne.

Fruit of the atom
by the Rev. Eric Jenkins.

Nuclear power — its development in the United Kingdom.
Book review.

FEBRUARY
Nuclear energy prospects
Dr. P.M.S. Jones to the West Midlands Productivity Association Conference on Energy for the Future.

A summary of the 1977 UNSCEAR report

MARCH
Nuclear power in the public eye
Sir John Hill to the Royal Society for the Encouragement of Arts, Manufactures and Commerce, in London.

Thermal reactor policy
Statement by the Secretary of State for Energy, Mr. Tony Benn, to the House of Commons.

The Windscale CAGR handling rig — 10 years' testing
by M.E. Ginniff.

The management of Canada's nuclear wastes
Summary of a report.

APRIL
Nuclear power and the proliferation issue
Dr. Walter Marshall to the University of Glasgow (The Graham Young Memorial Lecture).

Nuclear power: advantages that outweigh the risks
by Sir St. John Elstub *et al.*

Nuclear power development and non-proliferation
Dr. Sigvard Eklund to the British Nuclear Energy Society.

MAY
Nuclear waste disposal
Sir John Hill to the Institution of Electrical Engineers.

UK research on underground waste disposal
Dr. Frank Feates and Norman Keen.

The Windscale Report
A review.

Nuclear power — The moral question
by Philip Searby.

Long-term options for the FR fuel cycle
Dr. R.H. Flowers, K.D.B. Johnson, Dr. J.H. Miles and Dr. R.K. Webster to the Fifth Energy Technology Conference in Washington.

JUNE
Status Report on Fusion
by the International Fusion Research Council (IFRC).

Nuclear power and the environment
Sir John Hill to the British Institute of Radiology (Sylvanus Thompson Memorial Lecture) in London.

Energy Today and Tomorrow
Report of a conference organised by four women's organisations at Central Hall, Westminster.

Environmental Protection
NRPB Report R71.

Nuclear power and the environment: CBI comments

Electricity Supply Reorganisation
The White Paper.

JULY
Nuclear waste disposal: the geological aspects
by Dr. N. Chapman, Mr. D. Gray and Dr. J. Mather.

Electricity — new possibilities for generation and use
Sir Francis Tombs to the Royal Society of Arts.

Windscale Development Order Debate
House of Commons.

AUGUST
Low level radiation effects: the Mancuso Study
A review by Dr. J.A. Reissland and Dr. G.W. Dolphin together with a comment by Dr. Leonard A. Sagan.

Vibration in nuclear plant
A report on the Conference on Vibration Studies by M.E. Ginniff and C.H. Jones.

Energy 2000
Report of a British Institute of Management conference by John Sargeant.

Underground waste disposal
A review by Dr. J.B. Lewis of a report by M.D. Hill and P.D. Grimwood (NRPB).

The risks of energy production
A comment by Dr. P.M.S. Jones on the Inhaber Report.

Alternative sources of energy — the White Paper.

CEGB Corporate Plan

SEPTEMBER
Proliferation and the recycling of plutonium
Dr. Walter Marshall to the Uranium Institute in London.

Geothermal energy and the UK
by Dr. J.D. Garnish.

"The Self-Splitting Atom"
A review by Dr. Joan Freeman of the history of the Rutherford-Soddy collaboration by Dr. Thaddeus J. Trenn

OCTOBER
24th Annual Report of the UKAEA

Renewable sources of energy — the prospects for electricity
Glyn England, Chairman, CEGB, to the staff at Fawley oil-fired power station, Southampton.

Uranium supply and demand
A report by H. Hunt of the Uranium Institute's 3rd Annual Symposium.

BNFL Annual Report

Nuclear power: the moral question

Nuclear power costs
A commentary on the Ryan Report.

International energy supply
A review of a report by the Rockefeller Foundation

CEGB Annual Report

NOVEMBER
The uranium market — economic and political factors
by Terence Price.

Decommissioning nuclear reactors
by W.H. Lunning

The discovery of fission
by Dr. H.A.C. McKay.

The Radiochemical Centre Limited Annual Report

Major planning inquiries

DECEMBER
Reactor accidents and the environment
by R.F. Griffiths *et al*

The economics of nuclear power
by H. Hunt and G.E. Betteridge.

The Nondestructive Testing Centre
by R.S. Sharpe.

Fuel — the broader perspective
Sir John Hill to the National Energy Management Conference in Birmingham.

Critical comment on the Mancuso Study

Ionising radiations regulations