PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Environmental Aspects of the Fast Reactor Fuel Cycle [and Discussion]

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Environmental aspects of the fast reactor fuel cycle

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The main characteristics that differentiate a developed fast reactor fuel cycle from the thermal reactor fuel cycles operating now are the higher fissile content of the fuel, the greater incentive to reprocess fuel at shorter delay times and the elimination of uranium mining. The local and global environmental impacts of a typical fuel cycle normalized to 1 GW_e a of output are estimated, including those from the fabrication, transport and reprocessing of fuel and from reactor operations. Radioactive emissions and radiation doses arising from these operations are compared with those from thermal reactor cycles. The risks of accidental discharges from reprocessing plants are discussed, but reactor accidents are not included. The requirements for safeguards are described. Typical inventories of radioactive wastes arising from reprocessing and from decommissioning have been calculated; the management and disposal of these wastes will pose no significant new problems. The overall result is that a transition from thermal to fast reactor fuel cycles should not result in any increase in environmental impact.

1. Introduction

This paper is concerned with the local and global environmental impacts of a developed fast reactor fuel cycle, excluding those due to possible reactor accidents, which is the subject of Dr Hennies's paper (this Symposium). Since the world has accumulated considerable experience of thermal reactor fuel cycles, a reasonable approach to an estimation of the environmental effect of a change to a fast reactor economy is to examine the difference between fast and thermal fuel cycles. While the detailed calculation of impacts will depend on the fuel chosen and on the irradiation and reprocessing régime, some broad characteristics will hold for any fast reactor cycle: (1) uranium mining is eliminated; (2) the fissile content of the fuel is increased by a factor of 4 and plutonium replaces ^{235}U; (3) reprocessing is essential to recover fissile material at some stage; (4) the actinide content of the eventual wastes is increased.

The environmental impact considered in this paper is the risk to human health. Comparisons with thermal fuel cycles can be made by drawing on the comprehensive surveys made by the United Nations Scientific Committee on Atomic Radiation (UNSCEAR) in their 1982 and 1988 reports. A comparison of the environmental consequences of fast and thermal fuel cycles was earlier made as part of the International Fuel Cycle Evaluation Exercise (INFCE) (IAEA 1980). More recently, many of the parameters of a typical fast reactor fuel cycle were described and examined at the public local inquiry held into the proposal to site a dedicated fast reactor reprocessing plant (European Demonstration Reprocessing Plant (EDRP)) at Dounreay in Scotland in 1986. Much of the material in this paper is drawn from work done on the design of EDRP and on the design parameters of a commercial fast reactor based on the recent European development, EFR. The illustrative figures in this paper are based on studies of a

reactor which would have a heat output of 3.6 GW and a net electrical output of 1.4 GW; at a load factor of 70 %, the yearly output would be 1 GW_e a†. The reactor core would contain some 45 t of uranium and plutonium as mixed oxide (*ca.* 19 % Pu) and the axial and radial breeders would contain about 34 t of uranium as uranium dioxide, UO_2. Although detailed figures for isotopic composition and fission product and actinide inventories would change for a different type and enrichment of fuel and fuel burn-up, the broad trends to be expected as the world moves from thermal to fast reactors can be gauged by comparing the fuel cycle of such an oxide-fuelled fast reactor with that of typical reactors in commercial use today, such as a pressurized water reactor (PWR) using 3 % enriched uranium oxide fuel. All the figures given below are normalized to an output of 1 GW_e a unless otherwise described.

2. Fuel: composition and management

The basic data required for the estimation of environmental risks are the quantities of radioactive isotopes to be handled and eventually disposed of. These arise mainly from the fission process in the fuel itself. The fuel cycle for a fast breeder reactor (FBR) is virtually self-contained, with an input of about 1.2 t of depleted uranium required for every 1 GW_e a generated, compared to some 200 t of fresh uranium for a once-through PWR fuel cycle. The proposed operating régime involves shutdown every two years for refuelling and inspection, at which time one-third of the core and radial breeder assemblies would be transferred to internal storage for initial decay heat removal. The fuel dwell time will then be six years in the reactor core and two years in internal storage before transfer to the reprocessing plant. Such a régime would give a mean fuel burn up of 17 % and a peak burn-up of approximately 4 % in the breeder. A materials flow chart for the fourth cycle through the reactor is shown in figure 1

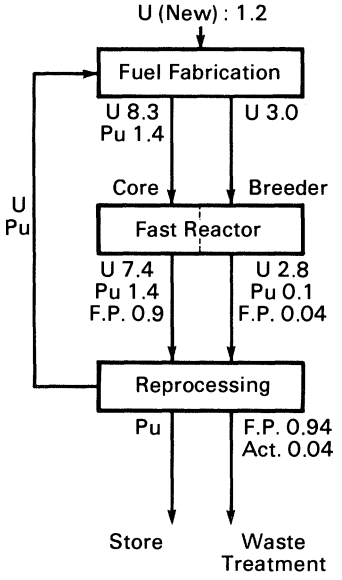

FIGURE 1. Material flows t$(GW_e\ a)^{-1}$ through the core and breeders of a typical fast reactor. All figures are in tonnes.

† The symbol 'a' denotes 'year'.

(Powell & Tyler 1989); it has been assumed that the radial and axial breeder material will be processed together.

The isotopic composition of the plutonium will not change markedly beyond the first fuel cycles, and can be compared with that of the initial plutonium assumed to be PWR plutonium after high burn-up (*ca.* 30000 MW d t^{-1}) stored for four years after reprocessing. Such a comparison with the first and fourth fast reactor cycles is given in table 1 (Powell & Tyler 1989). The concentration of ^{239}Pu increases somewhat above the original value while that of the higher isotopes decrease.

TABLE 1. ISOTOPIC COMPOSITION OF PLUTONIUM IN SUCCESSIVE FUEL CYCLES

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
half-life/years	87.8	2.4×10^4	6.6×10^3	14.4	3.8×10^5
PWR Pu (%)	2	54	26	10	8
after 1st cycle (%)	2	61	26	4	7
after 4th cycle (%)	1	64	27	4	4

The total quantity of fission products resulting from the generation of 1 GW_e a should be smaller for a fast reactor than for a PWR because of the higher thermal efficiency assumed for a fast reactor. The fission product inventory from the fourth reprocessing cycle of a fast reactor has been compared with the inventory in PWR spent fuel (Powell 1989; Flowers *et al.* 1986). As would be expected, the plutonium, americium and curium activities are higher for a fast reactor, and the uranium activities lower. Activities of ^{135}Cs and ^{151}Sm are significantly higher for a fast reactor case, while those of ^{90}Sr and ^{85}Kr are lower.

(*a*) *Fuel reprocessing and fabrication*

The chemical reprocessing of fast reactor fuel and the fabrication of fresh fuel elements from the recovered uranium and plutonium is described in another paper in this Symposium (R. H. Allardice). The environmental consequences of the emission of gaseous or liquid effluent from reprocessing and fuel fabrication plants are described in this section, leaving fuel transport and solid waste disposal to later sections.

What discharges are allowed from plants will primarily be determined by the mandatory requirement to reduce radioactive content to levels 'as low as reasonably achievable (the ALARA principle), within allowable maxima set by the regulatory authorities. There must come a point where the additional expense, additional on-site storage and consequent radiation exposure, and the additional volumes of solid waste for disposal generated by another treatment plant, are not justified by a marginal lowering of the gaseous or liquid effluents. What this point may be will depend on the geographical location of a reprocessing plant. The case made for the EDRP at Dounreay is typical of a plant situated on the coast in a location where there is a high dilution factor in the receiving water. The effluent figures and exposures calculated for this case can be compared with those for other plants.

The most exposed group (the critical group) from the effects of liquid effluent from the existing Dounreay site have been found to be persons who eat 5.5 kg of winkles a year and spend 530 h on the foreshore in the vicinity of the plant. Doses to these critical groups in 1987 totalled about 0.03 mSv† (Hunt 1988). A similar critical group close to the Sellafield thermal reprocessing plant received 0.35 mSv in 1987, though the doses due to discharges from

† 1 Sv $\approx 2 \times 10^{-3}$ C kg^{-1}.

Sellafield are reducing due to the installation of additional treatment plant. UNSCEAR (1982) based their model thermal oxide reprocessing plant on the expected performance of the THORP plant at Sellafield and calculated a radiation dose to the critical group of 0.22 mSv a^{-1}, or *ca.* 0.02 mSv $(GW_e\ a)^{-1}$. Three separate calculations of the doses to the critical group arising from a fast reactor reprocessing plant similar to EDRP situated at Dounreay were in close agreement and estimated doses of 0.003–0.004 mSv $(GW_e\ a)^{-1}$ while the same discharge data applied to the Sellafield site would cause a maximum dose of 0.02 mSv $(GW_e\ a)^{-1}$ (Powell & Tyler 1989).

Estimated doses to small critical groups are very dependent on the information about local habits. Possibly greater significance can be attached to the estimates of collective dose commitment to the regional population, which is a measure of the radiation burden on that population. Calculations have been carried out for a typical fast reactor reprocessing plant similar to EDRP using the same assumptions as those adopted by UNSCEAR (1982) for a model oxide reprocessing plant (Powell & Tyler 1989). The estimates are compared in the first two columns of table 2. In each case, a regional population of 260 million is considered, and the doses would have been received in less than 500 years.

TABLE 2. NORMALIZED COLLECTIVE DOSE COMMITMENT FROM REPROCESSING AND FUEL FABRICATION

(manSv $(GW_e\ a)^{-1}$)

	FR plant	model thermal case (UNSCEAR 1982)	thermal 5% reprocessing (UNSCEAR 1988)
fuel fabrication	0.019	2×10^{-3}	3×10^{-3}
fuel reprocessing			
atmospheric, ^{3}H, ^{85}Kr, ^{14}C, others	0.046	0.34	0.073
aquatic, ^{137}Cs, ^{106}Ru, ^{90}Sr	0.053	0.7	1.2

In its 1988 report UNSCEAR has abandoned the concept of a model reprocessing plant on the grounds that all fuel may not be reprocessed. Instead normalized discharge data for the years 1980–85 inclusive from Sellafield and Cap de la Hague were used to calculate collective doses. It is then assumed that only 5% of fuel will be reprocessed, and in the absence of information no estimate was made of dose from the unreprocessed fuel. The collective doses so calculated are also shown in table 2. It should be noted, however, that discharges from the thermal fuel reprocessing plants are reducing rapidly; for example the discharge of ^{137}Cs in liquid effluent from Sellafield fell by an order of magnitude between 1980 and 1985.

The higher figures for doses from fuel fabrication for fast reactors reflect the discharge of some actinides to atmosphere. Most of the differences in doses from reprocessing plants are due to the much lower production of ^{14}C in fast reactors, and to the lower figures now assumed for liquid effluent discharge from fast reactor reprocessing plants, which reflect the advances made in effluent clean-up systems. It should be noted that lower figures for discharges from thermal fuel reprocessing have been quoted for inland reprocessing plants than those used by UNSCEAR (RWMAC 1984). Strictly, the fact that a plant reprocesses fuel from a fast reactor rather than from a thermal reactor has no direct effect on the level of discharge in each case.

But these comparisons show that the planned discharges from fuel reprocessing using technology available now are already lower than those of comparable plant today.

(*b*) *Accidental discharges*

As well as considering effluent levels during normal operation of the plant, it is necessary to consider the possibility of accidents. As in any plant, accidents can happen as a result of several initiating events: external hazards, such as aircraft crashes and earthquakes; loss of site services; internal events, such as fires or criticality incidents; random failures of equipment; human error.

The philosophy of protective measures applied to plants is exactly the same as for reactor accidents, which are dealt with by Dr Hennies (this Symposium). To estimate the risk, it is necessary to calculate the possible frequency of a release of radioactivity, and the size of the release. The estimation of consequences then follows from the application of dispersion equations in the same manner as for normal releases (Brown 1986). The calculations are set out in the form of event trees and fault trees.

The heavy shielding that is necessary around those parts of the plant handling large amounts of radioactivity is itself a good protection against ordinary chemical accidents and against some external hazards. One type of accident that must also be considered in a chemical plant reprocessing nuclear fuel is a criticality accident, due to the concentration in one place of too great amounts of fissile material. Criticality accidents could lead to local disruption of the plant and to hazard to anyone close to them, but probably not to a serious spread of activity. They can be prevented by appropriate design ('ever-safe shapes'), by good monitoring of fissile concentrations and by the incorporation of neutron-absorbing material.

External hazards due to extreme weather or to earthquakes have to be assessed for each site. Aircraft crash is another universal hazard, which again can be reduced by proper siting. There would be no possibility of a light aircraft or a heavy aircraft at landing speed penetrating the concrete shielding surrounding plant areas carrying high radioactive inventories. However, a heavy plane at high speed might break the containment, but the probability of a direct impact on the small area of a plant that might involve a release of activity is low and additional protection could be provided if required (Brown 1986).

Internal hazards due to protective equipment failure or to human error in operation or in maintenance can be minimized by design and by formalized examination of operating procedures. Quite in general, the consequences of a local failure in a reprocessing plant will be low since release of more than a small fraction of the total radioactive inventory from any part of the plant is virtually impossible because there is no driving force in the plant capable of dispersing large quantities of material even if the containment is breached, other than fire or explosions. This general property of reprocessing plants, coupled with the time usually available for remedial action, was noted by the Health and Safety Executive in their recent safety audit of the reprocessing plants at Sellafield (HSE 1987). Conditions capable of causing fire and explosion are minimized by excluding materials of low flashpoint, by eliminating points of ignition and by incorporating fire retardation devices.

The time for remedial action is particularly important in the case of the accident that might cause the largest release, namely, the loss of cooling water to the tanks containing the highly active liquor after reprocessing. The heat is removed from these tanks by circulating water through cooling coils and rejecting the heat to a secondary cooling circuit, and all safety circuits

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are duplicated. Loss of electrical power to all the pumps or complete loss of all water supplies would lead eventually to overheating of the tanks. The consequences would depend on the inventory in the tanks and on details of the design. In an extreme example (Brown 1986), a tank would heat to boiling in the order of a day in the absence of any cooling, and then boil dry in the order of a week; dry-out could be prevented by the addition of water or nitric acid. Although dry-out would be followed by a serious release of radioactivity, it is hardly credible that no action could be taken within this time to reinstate cooling or to protect the population at greatest hazard. It could perhaps be argued quite generally that the stage in the fuel cycle when the contents of the spent fuel is dispersed in liquids is the most exposed to dispersion by breakage or external hazard and that storage in liquids should not be prolonged. While the radioactivity is locked in a solid form, either as spent fuel or as vitrified solid waste, stores can be designed to be capable of being cooled by natural convection with no external power required, and the possibility of dispersion is much reduced.

To summarize, although a complete analysis of the risk arising from plant accidents can only be made after a full design study, preliminary analysis of the EDRP outline design indicated that individual risks could be held to less than 10% of those arising from routine operations, i.e. a risk less than 10^{-7} a^{-1} for members of the public (Brown 1986). The possibility of any accident to a plant giving rise to radiation doses sufficiently high to cause early health effects (radiation sickness) is very remote. Societal risk, either to a regional or global population, will also be expected to be low and no more than that calculated for normal operation of the plant.

(*c*) *Public examination of the safety case*

The safety case for reprocessing plants has been examined in public in the U.K. on two occasions: the Windscale Inquiry in 1977 and the EDRP Inquiry in 1986. It seems worthwhile to summarize the major matters affecting environmental impact that were raised, to point to questions that will have to be attended to in any subsequent proposal for new plants. Most of these examples are taken from the 1986 inquiry since this was explicitly concerned with a fast reactor fuel cycle and the application of formal risk analysis methods had become more established by that time. A useful summary of the arguments is in the draft report published by the Chief Reporter (Bell 1987); the final report is not yet available.

Much of the argument at both public inquiries was concerned with general matters affecting nuclear power sites and with questions that related to particular sites, including:

(i) the validity of the regulations governing radiological safety standards;

(ii) the application of radiological safety standards to small groups who may be especially vulnerable;

(iii) the definition of local critical groups and the adequacy of local monitoring;

(iv) the adequacy of emergency plans in the event of a serious accident.

There is no special attribute of a fast reactor fuel cycle that has to be taken into account when such questions are considered. Safety standards in all nuclear installations must be sufficiently high so that other local activities are not affected.

The analysis of the risks of accidents was also subjected to long scrutiny at the EDRP Inquiry, though a full safety analysis by probabilistic risk analysis (PRA) methods was not available. The highest risks from the proposed plant were seen to arise from the two areas with the highest inventory of radioactive material: the fuel store and the high active liquid (HAL) storage tanks.

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Of these the HALS tanks are the more vulnerable; the draft report states that it would be a matter of detailed design to ensure that the cooling systems included sufficient diversity, redundancy and segregation of vital components to give adequate protection against common mode failure. The conclusion in the draft report (which is, of course, subject to revision) is that 'having regard to the timescale of the overheating process, it appears that the only mechanism for a massive release of radioactivity is sabotage of the cooling system in circumstances which preclude remedial intervention. In the absence of such an attack, it seems inconceivable that one of the many ways of restoring cooling to the tank could not be achieved within 6 days' (Bell 1987).

Other points raised in the Inquiries concerned the efficiency of safeguards against proliferation of nuclear weapons, the safety of transport of fuel and waste disposal plans. These are discussed in the following sections.

3. Safeguards

The question of diversion of fissile material from civilian to military use has been raised both at the Sizewell Inquiry (1987) and the EDRP Inquiry.

There are two different questions to be addressed. One is the possibility of theft of fissile material by a subnational group or individual and the other is the diversion of material from civilian to military use by the state. This latter threat is the subject of international safeguards. Within the European Community, these safeguards are applied by Euratom and by the IAEA, and in the rest of the world by the IAEA alone. The problem of applying safeguards to plutonium fuel cycles has been the subject of research by IAEA, Euratom and member states for many years, and techniques of surveillance, item accountancy and nuclear materials accountancy have been developed. Enhanced containment and surveillance implies the use of video cameras and seals of high reliability. Item accountancy involves a check on the numbers of individual items, their identity and their integrity. Non-destructive assay can be used to measure the quantity of plutonium in unirradiated fuel assemblies at frequent intervals while they are in store before being loaded into the reactor.

At the fuel fabrication and reprocessing plants, use can be made of 'near real time' nuclear materials accountancy (NRTNMA) in addition to techniques of surveillance and non-destructive assay. NRTNMA involves the frequent accounting for all the plutonium present in the plant and the study of trends in the successive accounts by using statistical techniques. A particular point is the plutonium available from the blanket, which will be of higher military grade than the plutonium in the reactor core. Safeguards monitoring could be applied to ensure that the plutonium from the blanket is mixed with that from the core before final purification.

A concomitant of the increased total plutonium inventory will be an apparent increase in the hypothetical amounts of material unaccounted for (MUF). This can be counteracted to some extent by improved techniques to reduce the already low accountability errors in the chemical reprocessing part of the fuel cycle. At present, mass accountancy can be achieved at a level of error of about 1 in 10^4. Current chemical assay accuracy amounts to perhaps 1 in 10^3. However, by far the greatest current uncertainty lies in the area of reactor physics predictions with current plutonium production estimates having errors somewhat greater than 1 in 10^2. Thus it is clear that the 'in-reactor' component of the cycle will provide the greatest level of

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uncertainty regarding the plutonium inventory. However, this part of the cycle is the most inaccessible for diversion and that in which unit accountancy (for example, by numbers of subassemblies) is most readily achieved.

Perhaps of more concern is the threat of diversion by unauthorized or by terrorist groups (RCEP 1977). It has been said that a fast reactor fuel cycle is particularly vulnerable to such a threat because of the large amounts of plutonium in the cycle. However, while the total amount of plutonium in the cycle will be larger than in thermal fuel cycles, the amount that is accessible will not necessarily increase since a main economic objective will be to minimize the time the plutonium spends outside a reactor. Protection is a matter for national security, and affects the use of plutonium in thermal reactors, which is now increasing, as well as in fast reactor fuel cycles. Plutonium will have to be carefully accounted for at every stage in the cycle, particularly in transit. These questions will have to be addressed as plutonium is shipped from present plants. In a mature system, adoption of the nuclear park concept with all the fast reactor fuel cycle contained within the environs of a single site would improve protection against this type of diversion by the use of well-established containment and surveillance techniques.

4. Transport

In a developed fast reactor economy, transport of spent fuel may still be required to a plant at which it is reprocessed and the recovered fissile material used in the manufacture of fresh fuel. The fresh fuel would then be transported to the reactor. In an interim stage, as at present, fissile material has to be transported from a reprocessing plant to a separate fuel fabrication facility. The criteria of stringent tests that have to be satisfied by the design of the 'flasks' used to transport radioactive material have been laid down by the IAEA and the regulations are administered in this country by the Department of Transport. The record of safety of transport by rail, road and sea has been excellent. Designs of flasks for transporting fast reactor fuel are discussed by R. H. Allardice (this Symposium).

Accidents are unlikely and the consequences, if they should occur, would be small. Brown (1986*b*) estimated the frequency of loss of a ship at sea en route to the proposed EDRP as between 10^{-3} and 10^{-4} per year, but considered that the massive fuel flask would survive intact or, at most, suffer slight damage that would cause a slow leak of radioactivity. The packages should be recoverable from all but the deep ocean. The collective dose to the British population resulting from a leaking flask was estimated to be below 0.8 manSv, which is 10^{-5} of the collective dose from natural background every year.

Separated plutonium, as oxide, would be transferred to a fuel fabrication plant in another location by air rather than by land or sea on the grounds of better security. The container that would be used would be extremely strong. A reasonable estimate of accident frequencies can be made from the historical record, at about 1.2×10^{-6} per flight (Brown 1986*b*), and about 60–80 % of these may occur during landing and take-off. It is estimated that the package containment system could only be breached by an ultra-severe impact, in those rare accidents where control is completely lost at high altitude leading to a rapid descent. Even then, the package should survive impact onto soil or constructional materials and only be breached if high-speed impact occurred on a very resistant surface such as massive rock. The chance of such a crash has been estimated as less than 2×10^{-8} per trip. The consequences of such an unlikely crash would not be serious. Plutonium dioxide is an inert material, not easily dispersed.

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Calculations of possible releases indicate that an individual 400 m from the crash might incur a risk of later death from cancer of about 2×10^{-3} and that such a release in a suburban location might affect the health of 100 people or more with a probability of 10^{-3}. Given the very low probability of any release at all, this is a small order of risk (Brown 1986*b*). The transport of civil plutonium by air has recently been reviewed by the Advisory Committee on the Safe Transport of Radioactive Materials (1988). The Committee concludes that the health risk from current transport to and from the U.K. is extremely remote and acceptable, and stresses the importance of an international consensus on safety standards.

5. Waste management and waste disposal

The gaseous and liquid discharges amount to a very small proportion of the total radioactivity produced in the fuel cycle. More than 99.9 % of the activity will eventually arise as solid waste of one sort or another, and more than 95 % will end up in the high level waste (HLW). As in all other nuclear operations, low-level solid wastes (LLW) will be generated at all stages in the cycle, and intermediate level waste (ILW), such as fuel cladding and very active reactor components, will come from particular parts of the cycle and arise at decommissioning.

Methods of management and of storage of all classes of waste have been developed and the treatment of fast reactor wastes will raise no new matters of principle. The main differences between wastes from fast and thermal reactor systems are due to

(i) the increased quantity of plutonium to be processed per GW_e a;

(ii) the higher burn-up of irradiated fuel in the reactor;

(iii) the use of sodium as the reactor primary coolant.

The increased quantity of plutonium in the cycle will give rise to increased volumes of plutonium-contaminated wastes. The high burn-up and high fuel rating of fast-reactor fuel results in higher levels of activity at discharge, though this effect is not significant after a few years' cooling.

The volumes of wastes generated will depend on details of the processes actually used but are unlikely to be very different from those in those thermal reactor fuel cycles in which the fuel is reprocessed. The volumes of HLW will be small, about 3 m^3 $(GW_e\ a)^{-1}$ after vitrification, and similar to those from thermal reactor fuel reprocessing, since in each case the volume simply depends on the fission product loading of the glass blocks. The α-activity associated with ILWs from fuel reprocessing may be higher by a factor of 2–5 (RWMAC 1984), but the total waste volumes arising over the design life of the reactors will be similar (RWMAC 1984; Kenny 1986). About 30000 m^3 of ILWs and LLWs combined will be produced over the lifetime of a reactor of 1 GW_e capacity, counting wastes arising from reactor operations, reprocessing of fuel and decommissioning. In addition, some 4000 t of slightly contaminated sodium will have to be disposed of when a fast reactor is decommissioned. The nuclides present will be ^{137}Cs and ^{22}Na. Studies of alternative options indicate that neutralization and ion exchange treatment followed by direct discharge to sea would be adequate, with a liquid effluent of specific activity lower than that from the proposed reprocessing plant.

The thermal reactor fuel cycles will also generate large volumes of mining and mill tailings waste from uranium mining. These contain all the radioactive species in the uranium decay chain from ^{230}Th downwards, and typically about 10 % of the original uranium. The total activity remaining in the ore wastes would then be about 30 TBq after the extraction of the

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200 t of uranium required to fuel 1 GW_e a in a thermal reactor, assuming no recycling. Assuming a concentration of uranium in the ore of 0.15%, there would be 130000 t of mill tailings produced every year, with a specific activity of 2×10^{-4} TBq t^{-1}, within the formal definition of LLW. These quantities are far larger than any others in the fuel cycles.

(a) *Disposal of high-level and long-lived wastes*

The HLW will be vitrified and long-lived ILW encapsulated in cement. Both will ultimately be consigned to deep repositories in suitable geological strata. Before any such disposal can be authorized, it must be shown by measurement and calculation that radioactivity will not get back to man in sufficient concentration to cause the most exposed individual to exceed the prescribed limiting annual risk, that associated with a dose of 0.1 mSv a^{-1} (DOE 1984). The radioactivity can only move in groundwater and it must be shown that the efficiency of the successive barriers to the migration of each radioisotope in the waste is adequate.

Such calculations depend on the decay curve of the constituents of the waste. Figure 2 shows the activity in HLW from fast reactor fuel after 1 GW_e a of electricity generation, plotted against time. Reprocessing was assumed to have occurred after $2\frac{1}{2}$ years cooling, with removal of 99.5% of the plutonium. Also plotted in figure 2, for comparison, is the total activity in unreprocessed PWR fuel, also normalized to 1 GW_e a, and the activity in the equivalent quantity of natural uranium ore needed to fuel 1 GW_e a in a PWR, i.e. the activity of 200 t of natural uranium in radioactive equilibrium with all its decay chain. All these calculations were carried out using the FISPIN series of codes (Burstall 1979).

Several deductions may be made from figure 2. First, the total activity to be disposed of from fast and thermal fuel cycles is not very different, and removal of the plutonium by reprocessing

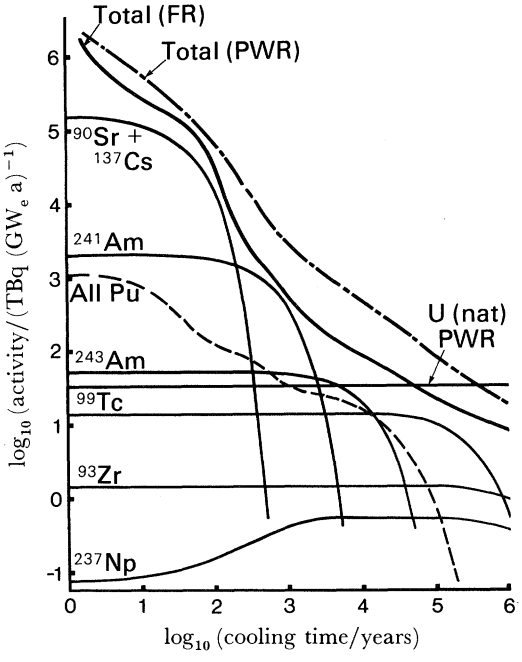

FIGURE 2. The radioactive decay curve of some constituents of high-level wastes from fast reactor fuels as a function of time after discharge. The HLW contains 0.5% of the plutonium after reprocessing. The decay curve for unreprocessed PWR fuel is included for comparison, as is the radioactivity of the natural uranium ore needed to generate 1 GW_e a in a PWR.

reduces the residual activity in a repository below that of unreprocessed thermal fuel. Secondly, the largest component of the activity for the first century or so comes from ^{137}Cs and ^{90}Sr, with ^{241}Am and ^{243}Am dominating from about 300 to 10000 years. Thirdly, the residual activity after 10^4–10^5 years is of the same order as that of the uranium ore that would be required for a thermal reactor fuel cycle, though the isotopic composition would be different.

This sequence is very similar to that for thermal reactor fuel cycles and the same sequence of barriers will be important (Flowers *et al.* 1986). The mobility of the actinide species can be reduced by chemical control since the actinides are very insoluble under alkaline and reducing conditions, which can be engineered by using enough cement as backfill material in a repository. It appears then that the waste disposal techniques being developed for the thermal fuel cycles would be directly applicable to the fast reactor case; the difference will be small.

6. Regional and global exposures

From the discussion in this paper, the local and regional environmental impact of a fast reactor economy should be of the same order as that from thermal reactor fuel cycles. The trend in recent years has been to reduce the radioactive content of all effluents and that will probably continue and not be reversed by a change to fast reactors. A summary of the local and regional collective dose equivalents to the public from all operations in thermal and fast reactor fuel cycles is given in table 3. The figures for the thermal reactor case in the first column are those

Table 3. Normalized collective dose equivalent commitments to the public local and regional contributions (first pass)[a]

	normalized collective effective dose equivalent commitment/(manSv(GW_e a)$^{-1}$)		
	UNSCEAR (1982)	UNSCEAR (1988)	FR
mining and milling[b]	0.54	0.3–0.4	0
reactor releases[c]	4.16	2.5	0.24
fuel reprocessing[c]			
atmospheric	0.3 }	1.27	0.06
liquid	0.7 }		0.05
transport	—	0.1	0.04
total	5.7	4.4	0.39

[a] 98% of dose delivered within five years.
[b] Population size 300 million; excludes dose arising from mill tailings.
[c] Population size 260 million.

given by UNSCEAR (1982) for a mixture of reactor types on many sites, and a comparative figure for reactor releases from a PWR on a coastal site such as Dounreay would reduce the dose from reactor releases to 0.51 manSv(GW_e a)$^{-1}$. The second column in table 3 is taken from UNSCEAR (1988), where the figure for doses from reprocessing relate to actual experience in the recent past, but, as already explained, on the assumption that only 5% of the fuel is reprocessed. The figures for the fast reactor cycle, in the third column, were calculated by Powell & Tyler (1989), using the approach described in UNSCEAR (1982).

It remains to estimate the global impact caused by the entry into the world's circulation system of long-lived radionuclides, namely tritium ^{85}Kr, ^{14}C and ^{129}I. These will cause

additional low radiation doses to large numbers of people, and calculations of the collective dose commitments integrated to infinity (10^8 years) were carried out by UNSCEAR (1982), together with similar calculations for doses arising from uranium mining and waste disposal. Similar calculations have been carried out, using the same assumptions, for the fast reactor fuel cycle described in this paper (Powell & Tyler 1989). The results are given in table 4. In the 1988 Report UNSCEAR reduced the collective dose commitment from mill tailings at 10^4 years to 150 manSv $(GW_e\ a)^{-1}$ and the total to 210 manSv $(GW_e\ a)^{-1}$, on the assumption of limited reprocessing as discussed above.

TABLE 4. GLOBAL CONTRIBUTION FROM OPERATIONS IN THE NUCLEAR FUEL CYCLE

	normalized collective effective dose equivalent commitment (manSv$(GW_e\ a)^{-1}$)			
integration period/years	10^1	10^2	10^4	10^6
thermal fuel cycles ^3H, ^{85}Kr, ^{14}C, ^{129}K	4.0	11.9	72	140
mill tailings				
(radon)	0.25	0.25	250	2800
(uranium)	—	—	460	460
high-level wastes	—	—	—	30
total	4.2	12.2	782	3330
fast reactor fuel cycle ^3H, ^{85}Kr, ^{14}C, ^{129}I	1.4	4.2	25	65
high-level wastes	—	—	—	(30)
total	1.4	4.2	25	95

The major advantage of the fast reactor cycle in the long term is due to the virtual elimination of uranium mining. It is not surprising that the collective doses due to mill tailings are larger than those due to waste disposal since the activities after 10^4 years are of the same order, as we have seen (figure 2), and the mill tailings are close to the Earth's surface, while the waste will be buried at depths of 300 m or more. Uranium mill tailings constitute the largest source of long-lived LLW in present-day nuclear technology. While the techniques of containment, consolidation and cover that are now being applied to mill tailings will ensure that local radiation doses due to them are below regulatory limits, access to the spoil will have to be restricted for as long as possible and, in the very long term, climatic and geological changes may well lead to dispersion of these wastes.

The overall result of the comparisons made in this paper is that a transition from thermal to fast reactor fuel cycles should result in a decrease rather than an increase in radiological environmental impacts.

We are much indebted to many of our colleagues for help in preparing this paper, especially to Mr G. R. Tyler and Mr H. Powell of Dounreay.

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Discussion

D. E. J. Thornton (*UKAEA, Risley, U.K.*). Why is it considered that the sodium inventory of a fast reactor will need to be disposed of on decommissioning, rather than reused.

L. E. J. Roberts, F.R.S. It is usually assumed that it will be disposed of, to ease the handling problem. Reuse, if it is possible, would reduce the environmental impact further.

A. Brandstetter (*Interatom, F.R.G.*). This disposal problem can be considerably relieved by removal of contamination. For example a caesium trap has been used at the KNK II reactor.

M. Y. H. Bangash (*Middlesex Polytechnic, U.K.*). Professor Roberts has considered a number of external hazards to nuclear reactors; however, in the present climate of public opinion it is essential to comment on all factors that are perceived to pose a threat. In particular, what are his views on the following.

1. The consequences of an aircraft crash on to the plant which can be considered in two groups according to the types involved. Our own research shows that low-mass high-speed military aircraft can cause severe damage to a structure than the heavyweight types such as the 747, which have lower deceleration on impact. It must also take into account the former engage in fast, low-flying exercises rather than adhering to fixed flight paths.

2. Portable missiles and explosives are now widely available. I have reported at SMIRT conferences the structural effects these can impart, they can certainly penetrate 2 m thick concrete and cause explosions inside reactor buildings. This hazard can surely not be dismissed as insignificant.

L. E. J. Roberts, F.R.S. The question of aircraft impact is not unique to fast reactors or to nuclear plant in general. It was considered in some detail at the public inquiry into the case

for the EDRP at Dounreay. It was agreed that a high-speed aircraft might breach the containment. However, the probability of a direct hit on a sensitive part of the plant is small, and analysis showed the consequences would not be great.

I have no information on the results of military action. However, the fact that fast reactors and associated plants are necessarily protected by thick concrete shielding means that they are less vulnerable than other installations containing hazardous substances such as petrochemicals, LNG and pesticides.

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