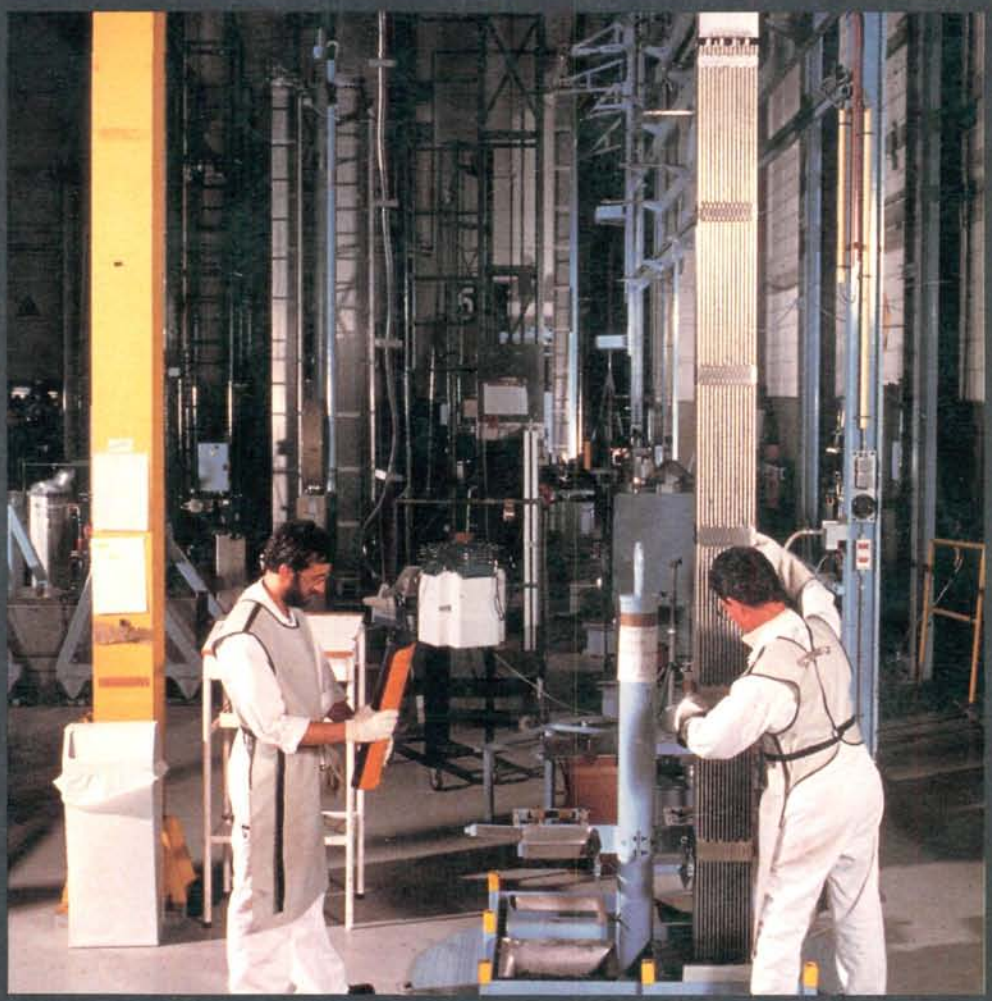
NUCLEAR ENERGY AGENCY

PLUTONIUM FUEL



AN ASSESSMENT

OCDE
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NUCLEAR ENERGY AGENCY

PLUTONIUM FUEL
AN ASSESSMENT

REPORT BY AN EXPERT GROUP

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971) and New Zealand (29th May 1973).

The Socialist Federal Republic of Yugoslavia takes part in some of the work of the OECD (agreement of 28th October 1961).

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan and the United States. The commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonisation of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

Several earlier Nuclear Energy Agency studies have looked at aspects of plutonium use. The Working Party on Nuclear Fuel Cycle Requirements, in *Nuclear Energy and Its Fuel Cycle: Prospects to 2025* (1) and earlier publications, have considered the regional and global implications for uranium demand of reactor and fuel cycle strategies, some of which have involved the use of plutonium in mixed uranium - plutonium oxide fuels (MOX) in both thermal and fast reactors. They have also estimated the quantities of plutonium that will be produced in spent thermal reactor fuel and the quantities that are likely to be separated from this fuel by reprocessing and stockpiled in OECD and other regions of the world over the next 35 years.

Other NEA working parties have looked in detail at the options for *Spent Fuel Management* (2), including fuel reprocessing and plutonium recovery, and at *The Environmental and Biological Behaviour of Plutonium and Some Other Transuranium Elements* (3).

The Study on *The Economics of the Nuclear Fuel Cycle* (4) completed in 1985 included some preliminary comments on the economics of plutonium recovery and its use in thermal reactor fuels, focussing on light water reactors (LWRs) but including the Japanese Advanced Thermal Reactor. It was during the course of this last study that the need for a more detailed review was identified, bringing together the latest views on the general characteristics of plutonium and the economics and logistics of its use, in a single easily understood booklet. The need for such a study has been strengthened by the steadily increasing use of mixed oxide fuels in thermal reactors in European OECD countries and Japan.

The present study has been undertaken therefore with three primary objectives:

(a) to set out simply and clearly the facts about plutonium and its present and future civil use;

(b) to explain the factors that influence decisions on the use or non-use of plutonium fuel in thermal reactors; and

(c) to illustrate how economic and material flow assessments of alternative fuel choices can be undertaken with stress on the situation over the next ten years.

Experts from eleven OECD countries and three international organisations participated in the Working Group; a full list is provided in Annex K.

The report has been prepared by the experts and does not necessarily represent the views of member governments or participating organisations, nor should it be taken to imply that all governments have definite views on the matters discussed.

ACKNOWLEDGEMENT

The Expert Group wishes to thank Belgonucléaire and the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan for their assistance with the core physics and economic calculations respectively.

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EXECUTIVE SUMMARY

Introduction

Ever since the 1950s, plutonium, used in fast reactors, has been seen as the key to unlocking the vast energy resource contained in the world's uranium reserves. However, the reductions in expected nuclear reactor installation rates, combined with discovery of additional uranium, have led to a lengthening in the perceived time interval before fast reactors, the most effective users of plutonium, will make large demands on plutonium supplies. There are several options concerning its use or storage in the meantime.

This report sets out the facts and current views about plutonium and its civil use, both now and in the medium term future. It explains the factors influencing the choice of fuel options and illustrates how economic and logistic assessments of the alternatives can be undertaken. Non-proliferation issues were specifically excluded from the study but the Working Group stresses their importance in decisions on the use and management of plutonium and spent nuclear fuel.

Nothing in the report contradicts in any way the general findings of the International Nuclear Fuel Cycle Evaluation concerning the use of plutonium or of the previous Nuclear Energy Agency study on the Economics of the Nuclear Fuel Cycle.

Background

Only minute quantities of plutonium occur naturally but it is an inevitable by-product of using uranium in thermal reactors. It is produced in all uranium fuelled reactors as a mixture of isotopes in ratios that depend on the composition of the initial fuel, the reactor type and the irradiation history of the fuel. Its in situ fission contributes significantly to the energy output of existing reactors.

Like many other materials plutonium is toxic when inhaled, ingested or when it enters the bloodstream through a wound. Although it is a hazardous material it poses no greater threat than many other materials utilised industrially. It can be handled safely with appropriate precautions and experience over the past 30 years has shown that it can be safely managed and used as a nuclear fuel.

Quantities of plutonium, both in spent thermal reactor fuel and as separated material recovered by fuel reprocessing, have been increasing for the past 30 years and will continue to increase in the future.

Interest is therefore being shown in the use of mixed plutonium - uranium oxide fuels (MOX) in thermal reactors, specifically LWRs, which use is steadily increasing in Europe and Japan. Already mixed oxide fuels are being used in 6 fast reactors and 13 thermal reactors in OECD countries.

This study restricts itself to the use of MOX as a thermal reactor fuel for existing types of LWR since this is the situation that will persist in the 1990s. The share of MOX fuel in the reactor core will be limited during the period to around 30 per cent, to ensure that reactor control and operation conform with the requirements of existing plant. Higher proportions could be used in the future in modified reactor cores or specially designed reactors.

Economic Assessment and Planned Use

It is concluded that the use of plutonium derived from past, present or contracted reprocessing, the costs of which have been paid or committed, in LWR MOX fuel offers utilities an economic saving of some 30 per cent compared with equivalent enriched uranium fuel in existing LWR reloads. An economic advantage would persist down to uranium prices as low as $50 per kg ($19 per lb U_3O_8). This is because effectively free plutonium replaces both fresh uranium and separative work costs and these more than offset the higher cost of MOX fabrication.

For this reason plans exist to extend the use of MOX made with "free" plutonium to some 40-45 existing LWRs (based on nationally assessed economic advantages), in France (16), Belgium (1), FRG (10 to 13), Switzerland (3) and Japan (10-12). To support these plans larger MOX fabrication plants exist or are being constructed in Belgium, FRG, France and Japan.

Early use of plutonium after reprocessing spent fuel minimises plutonium storage costs, minimises losses of fissile material due to radioactive decay and avoids the possible need to purify the plutonium chemically to remove americium prior to its use at a later date.

Of those countries represented on the working group the USA, Canada, United Kingdom and Finland have no current plans to use MOX fuel in thermal reactors. In the USA and Canada this is due to their assessment that it is not now economical to build and operate new spent fuel reprocessing plants to support thermal recycle, whilst in the UK there are as yet no operating LWRs. (There is currently no economic incentive to use MOX in advanced gas cooled reactors.)

Uncertainties

There remain uncertainties and differences of expectation concerning the future evolution of the costs of some of the stages of the uranium and MOX fuel cycles, particularly the back-end after removal of spent fuel from the reactor. These have little impact on the overall cost of uranium fuels for PWRs (as shown in earlier studies) or MOX fuels.

The report develops and explains the economic criteria which would need to be satisfied if reprocessing were to be undertaken specifically to recover plutonium and uranium for subsequent recycle in thermal reactors.

For plutonium recycle to be economic the difference between the costs of reprocessing (including conditioning, storage and disposal of reprocessing wastes) and the storage, conditioning and disposal of spent fuel should be less than the credits attached to the recovered plutonium and uranium when these are used as substitutes for fissile uranium-235 in thermal reactor fuel. (A small adjustment is needed to allow for the time lags in the fuel cycle.)

The credits for plutonium and uranium have values that differ with the expected front-end costs of MOX and enriched uranium fuel manufacture (uranium purchase, separative work, fabrication), and also with the delays in recycling and with decisions on the reprocessing of MOX itself. The back-end costs, which have not been examined in detail in this study, are not well defined where no commercial service yet exists. They will also differ from country to country depending on the scale of operations and local circumstances, although cross-border services may help to spread the benefits of economies of scale.

Thus a country which is currently uncommitted to reprocessing, and which did not believe it could reduce the net reprocessing costs below those of spent fuel storage, conditioning and disposal, would not see the construction of a new reprocessing plant solely for the recovery and recycle of plutonium and uranium in LWR fuel as economically attractive in the coming decade. (Net reprocessing costs here take account of credits for fissile materials recovered and waste storage, conditioning and disposal costs.)

A country with differing judgements about these costs might see the construction of future large scale reprocessing plants solely for thermal recycle of plutonium and uranium as economic.

Other Factors

However, economic issues are not the only ones which have to be taken into account in deciding on the use of MOX. In addition to the important political question of non-proliferation concerns there are strategic, environmental, safety and institutional factors to consider which are all important issues in determining fuel cycle strategies.

Use of plutonium in thermal reactors need not delay eventual fast reactor introduction although it could reduce their initial rate of penetration into the electricity supply system if separated plutonium were in short supply.

Because national circumstances and expectations differ, each country will wish to make its own evaluation in its own specific context, taking account of all the benefits and costs, both economic and non-economic, arising from the use of MOX fuels in LWRs.

INTRODUCTION

Plutonium is an inevitable by-product of the use of uranium fuel in nuclear reactors. It can be left in the spent fuel removed from the reactor, for storage or ultimate disposal, or it can be recovered by chemically reprocessing the fuel to separate the plutonium and remaining uranium from the other long lived transuranic elements and the shorter lived fission products.

Plutonium is of interest to the civil nuclear industry because it too is a nuclear fuel which can be used to augment or greatly expand the energy recoverable from the world's resources of low cost uranium. The most recent estimates (5) put "known" uranium resources recoverable at costs below $130 per kg U in countries outside the Eastern Bloc and China, at just over 3.7 million tonnes, although some 6-15 million tonnes of additional uranium may exist in analogous but as yet undiscovered "speculative" resources (6). The "known" resources would only be enough to run about one thousand 1000 MWe light water reactors for 25 years without uranium and plutonium recovery and recycle, or up to 40 per cent more with recycling. (The installed electrical capacity, nuclear and non-nuclear, in the same region is around 1.5 million MWe). Exploitation of higher cost resources or discovery and exploitation of speculative resources would increase the number of reactors that could be supported.

As will be discussed later, the use of plutonium in fast reactors can increase the energy recoverable from uranium by some 50 to 100 fold and this would convert the "known" low cost uranium resources into an energy source which is potentially greater than all the world's fossil fuels combined. Uranium could then, in principle, fuel the world's economies for millenia at costs not very different from those now experienced. The same is not true of oil, gas or coal.

At least until the late 1970s there were widely held fears that unless plutonium-fuelled fast breeder reactors were developed and deployed speedily, the industrial nations could face acute shortages of nuclear fuel with damaging consequences to their economies. Such a rapid deployment of fast reactors would require good initial stocks of plutonium extracted from spent thermal reactor fuels and several countries began building up stockpiles of plutonium in anticipation.

The worst fears of uranium shortages in the near future have receeded. Indeed in past few years there has been a glut which has depressed market prices. The rate of installation of nuclear plants has been less than was expected in the late 1970s and projections of future nuclear capacity have been revised downwards repeatedly (1). The nuclear slow down has been due in part to the world economic situation following the 1973 and 1979 oil crises and its effects on electricity demand. Additionally, exploration over the past 10 years has successfully proved the existence of additional deposits of uranium. The overall result has been that plutonium, which was seen as a scarce commodity, now looks like being in surplus in the foreseeable future.

Whilst both spent nuclear fuel and separated fission product wastes can be safely contained, stored and disposed of (2), some countries, for policy, technical, environmental or economic reasons, have preferred to reprocess spent fuel (or have it reprocessed by others). Indeed the existence of defined waste management arrangements based on reprocessing is a legal requirement for reactor licensing in some nations. Nuclear fuel cycle policies in some countries have therefore led to the creation of stockpiles of separated plutonium.

Several countries have been interested from the early days of civil nuclear power in ways of using plutonium to fuel thermal reactors, even though such use would have a much less dramatic impact on uranium requirements than its use in fast breeder reactors. In support of their interest a great deal of research and demonstration has been undertaken to prove the technology. In the current energy climate the surplus of plutonium from existing reprocessing plants and the delays in introducing breeder reactors have led some OECD countries to make use of plutonium in thermal reactor fuels rather than store it for exclusive later use in fast reactors. This practice may become more common within some OECD countries over the next few years.

The separation and use of plutonium does raise concern in some quarters about the implications for nuclear weapons proliferation. While this study recognises the importance of this issue it does not consider it further. The politically important question of non-proliferation aspects of the civil uses of plutonium was examined in great detail at the International Nuclear Fuel Cycle Evaluation (INFCE) of 1979-80 (7), the findings of which have been published, and it is a continuing topic of discussion at various expert group meetings under the auspices of the International Atomic Energy Agency. This Agency with co-operation from Euratom in the European Economic Community also operates the International Safeguards system designed to monitor the production, storage and movement of fissile materials to provide early warning of any attempts to divert material from the civil nuclear fuel cycle.

Members of the Expert Group believe that the current institutional arrangements and technological measures in place to guard against misuse of civil plutonium have been effective. In the future, as plutonium use increases, it will be important that they remain effective to ensure that the potential for increased proliferation risks is minimised while avoiding undue adverse impact on commercial activities.

The present study focusses on the medium-term use of mixed plutonium-uranium oxide (MOX) fuels in existing LWRs. It opens in Part 1 with a brief simplified description of the physical, chemical and toxicological properties of plutonium and its compounds. It continues in Part 2 with discussions on the ways in which plutonium can be used and the factors affecting choices. The later sections look at the costs of the separate stages of the mixed oxide fuel cycle and its overall economics and material balances. In Part 3 it describes the current position concerning MOX use in OECD countries. Finally Part 4 contains a summary and discussion of the results and presents the overall conclusions.

The study is intended as a general descriptive guide and is in no way to be considered prescriptive. The cost estimates are broadly based and do not necessarily correspond with those most appropriate for use in individual OECD countries. Nevertheless conclusions can be drawn that indicate the ways in which plutonium use may develop in the coming decade.

PART 1

THE OCCURRENCE AND PROPERTIES OF PLUTONIUM AND ITS COMPOUNDS

(A glossary of technical terms is provided at Annex I)

1.1 Occurrence of Plutonium

Plutonium is a chemical element whose atomic nuclei contain 94 positively charged protons together with about 145 electrically neutral neutrons. Atoms with different numbers of neutrons but the same number of protons in their nuclei are called isotopes and, whilst their chemical properties are the same, they have different radioactive decay behaviour and they differ in other important respects as will be seen later. Most chemical elements exist as mixtures of isotopes and plutonium is no exception.

Plutonium will have existed in the materials from which the earth was formed but the relatively short 24,000 year half-life of its main isotope, plutonium-239, means that, like carbon-14, any now existing on earth has to have been created subsequently by natural or man-made processes. Only the very long lived isotope plutonium-244 would have been expected to survive to the present era and traces have been recovered from Precambrian rocks in the USA (8). However, cosmic rays continuously replenish the earth's stock of carbon-14 and minute quantities of plutonium will also occur as isolated atoms due to neutron capture by naturally occurring uranium. The commonest uranium isotope, uranium-238, captures neutrons to become uranium-239. This is radioactive and decays to produce first neptunium-239 then plutonium-239. The neutrons initiating the reaction arise from spontaneous fission of uranium atoms or from cosmic ray or other radioactive decay induced reactions. Small quantities of natural plutonium-239 are found in uranium minerals due to these processes (10).

Small quantities of plutonium can be produced in the laboratory by bombarding uranium with alpha particles or neutrons produced using particle accelerators but its present existence in sizeable quantities is due to its production in nuclear fuel as a side-product of power production from uranium in nuclear fission reactors. If nuclear fusion reactors are eventually developed the neutrons released in the fusion process could also be used to produce plutonium from uranium.

1.2 Physical and Chemical Properties of Plutonium and its Compounds

1.2.1 Plutonium Metal

Pure plutonium in the bulk state is a hard silvery-white metal like cast iron which can be melted, moulded and machined into any shape desired. When alloyed with other metals it can be converted to a soft, maleable product which can be drawn into wire or rolled into thin sheets or foil. The stable form at normal temperatures (the alpha-phase) has a density of 19.9 g per cm^3 and a melting point of 640°C.

Plutonium is chemically reactive and oxidises rapidly in air. It is attacked by water vapour unless protected by an oxide film. Like many other reactive metals such as aluminium, magnesium or uranium it is stable in the bulk state but finely divided powders of all four are pyrophoric, i.e. they can catch fire spontaneously if exposed to air.

Because of its chemical reactivity metallic plutonium is normally handled in an inert atmosphere such as dry argon or nitrogen using glove box techniques and, where appropriate, remote handling equipment. The chemical reactivity and relatively low melting point of metallic plutonium, amongst other things, make it unsuitable for direct use as a reactor fuel. Indeed the metal is not normally produced as part of the civil nuclear fuel cycle. The product from reprocessing plants is either plutonium nitrate in aqueous nitric acid solution which must be processed within a short delay, or plutonium dioxide powder which can be stored until needed for the fuel fabrication process.

1.2.2 Plutonium Compounds

Plutonium combines with many non-metallic elements to form stable compounds. The oxides and nitrate are of particular importance in the production and transport of plutonium and its use as a fuel. The principal compound used in fuel is the dioxide which is a ceramic substance with a very high melting point (2390°C). It is blended with uranium dioxide to provide a mixed oxide or MOX. This may be done by mixing the pure oxide powders or by direct production of MOX from a mixture of the nitrates in solution. The fuels for thermal reactors contain around 5 per cent of plutonium whereas those for liquid metal cooled fast reactors have significantly higher plutonium contents of around 20 per cent by weight.

The carbide, nitride and metallic alloys have also been looked at as prospective fuel materials for fast reactors. The United States is re-examining metallic alloy fuels in connection with passively safe new modular fast reactor concepts and potentially improved reprocessing economics. The higher thermal conductivities and/or densities and harder neutron spectrum associated with these materials have advantages but these fuels are still some way from commercial adoption.

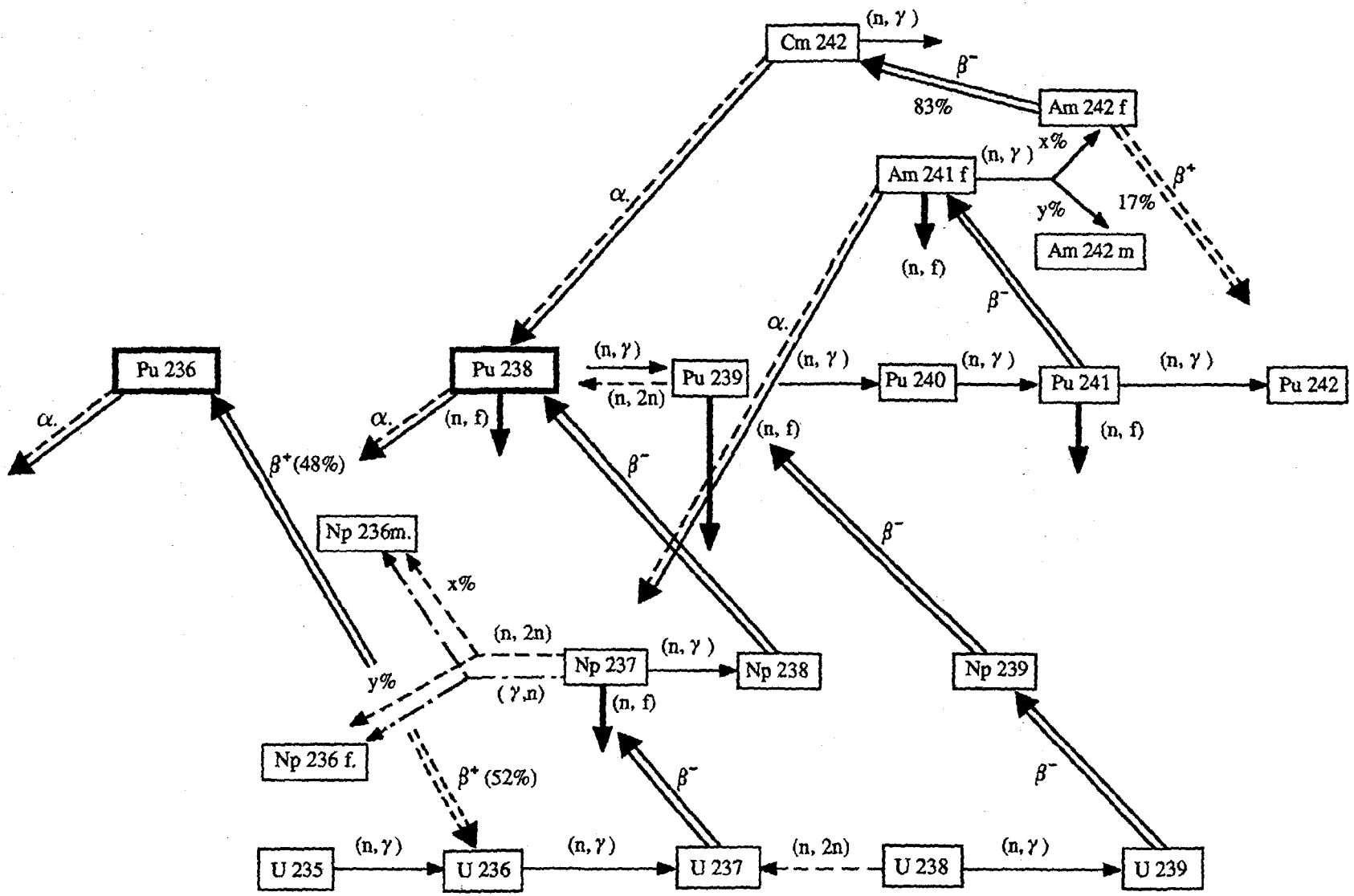
Plutonium has oxidation states of 3, 4, 5 and 6, and it can form compounds with differing relative solubilities in aqueous and organic media. This provides the basis for the solvent extraction methods used to separate uranium, plutonium and fission products in nuclear fuel reprocessing plants (2).

More detailed information on plutonium and its compounds is contained in references 8 (pages 499-839) and 9.

1.3 Plutonium Isotopic Composition

It has been noted in Section 1.1 that plutonium is normally produced in reactor fuel as a mixture of isotopes. The predominant isotope, plutonium-239 is produced by neutron capture in uranium-238. However, if a fuel element containing plutonium-239 is left in a reactor for any length of time further neutron capture can occur to yield higher isotopes like plutonium-240, plutonium-241 and plutonium-242. In addition, small quantities of two other isotopes, plutonium-236 and plutonium-238, are produced during the irradiation. These two isotopes are important because of their alpha, neutron and gamma activities or those of their daughter products. Their formation and decay are illustrated in the box below and Figures 1 and 2.

Figure 1. **SIMPLIFIED REACTION CHAIN FOR PRODUCTION OF Pu 236 AND Pu 238**



Legend for Figure 1

Pu 239 — Pu = Chemical symbol of element plutonium; 239 = Mass number of element

Am 242 f, Am 242 m — different "shape" isomers of Americium 242 (in particular, the "f" denotes a fission isomer)

α — alpha-particle emission (= 2 protons + 2 neutrons = helium nucleus)

β^- — negative beta - particle emission (a neutron emits an electron to become a proton)

β^+ — positive beta - particle (positron) emission (a proton emits a positron, i. e. a positively charged particle having the same mass as an electron to become a neutron. This is a relatively rare event)

γ — gamma emission

f — fission

β^- 83 % — probability of decay mode in per cent

n — neutron

(n, 2n) : capture of 1 neutron, followed by emission of 2 neutrons

(n, f) : capture of 1 neutron, followed by fission of atom

(n,γ) : capture of 1 neutron, followed by gamma emission

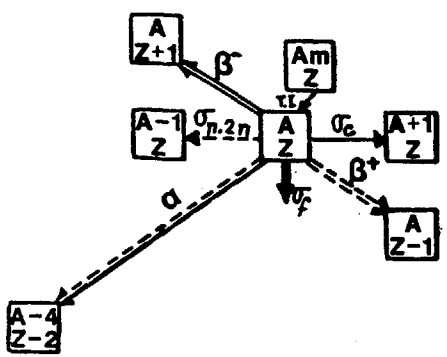
Figure 2. **DECAY MODES OF TRANSURANIC ELEMENTS**

Mode Indicator Diagram

This diagram illustrates the changes in Mass Number (A) and Atomic Number (Z) brought about by different modes of decay or transition.

The symbols $\sigma_{n,2n}$, σ_c and σ_f signify capture of 1 neutron and emission of 2 neutrons, capture of 1 neutron and fission, respectively. Beta, positron and alpha-particle emission are also illustrated.

T.I. indicates the transition of one isomer of an isotope into another. This is not strictly a decay.



Main Diagram

"α" in a box indicates that the main decay mode is by emission of an alpha particle. The associated arrows are suppressed to avoid confusion. The half-life for the principal decay mode is also shown at the bottom of each box. For some very long half-lives the notation "En" signifies "x·10ⁿ".

Plutonium-238 forms mainly:

a) in PWRs (UO_2) through the following successive reactions:

U-235 (n, γ) → U-236 (n, γ) → U-237 (β^-) →
Np-237 (n, γ) → Np-238 (β^-) → Pu-238

b) in FBRs and in MOX fuel:

Pu-241 (β^-) → Am-241 (n, γ) → Am-242 (β^-) →
Cm-242 (α) → Pu-238

Plutonium-236 forms mainly:

a) in PWRs (UO_2):

U-238 (n, 2n) → U-237 (β^-) → Np-237 (γ ,n)

or Np-237 (n, 2n) → Np-236m (β^-) → Pu-236

b) in FBRs and in MOX fuel:

U-235 (n, γ) → U-236 (n, γ) → U-237 (β^-) →
Np-237 (γ , n) or (n, 2n) → Np-236 (β^-) → Pu-236

References:

1. Etudes neutroniques des noyaux lourds formés dans le cycle du combustible des réacteurs nucléaires.
   Antonio Giacometti - Thèse de Docteur Ingénieur Orsay 1978.

2. "A methodology to evaluate (n, xn) cross section of fertile and fissile nuclei" - Proceedings of the International Conference, Santa-Fe (NM), May 1985, p. 1221. E. Fort - P. Long.

The process of neutron capture in and higher fissionability (see 1.6.1) of the plutonium isotopes with odd masses leads to accumulation of the less fissionable even mass isotopes if fuel is irradiated in a reactor for longer periods.

The mixture of plutonium isotopes in spent fuel leaving a reactor is therefore a function of the isotopic composition of the initial uranium fuel, the time for which the fuel is left in the reactor and the flux and energy spectrum of the neutrons, which differs with reactor design and operating conditions. The mixture of isotopes produced in a fast neutron reactor would differ from that produced by thermalised neutrons in a light water moderated reactor, such as the pressurised water reactor (PWR), due to differences in the propensities of uranium and plutonium isotopes to undergo fission and to capture neutrons at different incident neutron energies. (Figure 3, from ref. 11). Table 1 summarizes the isotopic composition of plutonium for a range of spent PWR fuels.

Figure 3(a). **NEUTRON CROSS-SECTIONS FOR URANIUM TO FISSION**

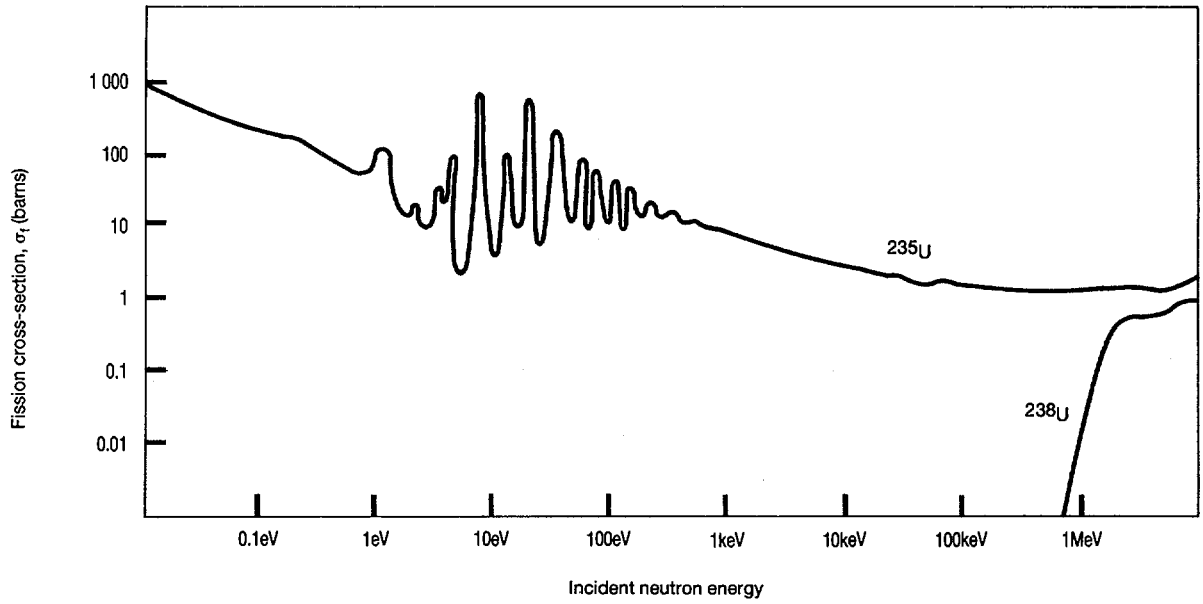


Figure 3(b). **NEUTRON CROSS-SECTIONS FOR URANIUM TO CAPTURE A NEUTRON**

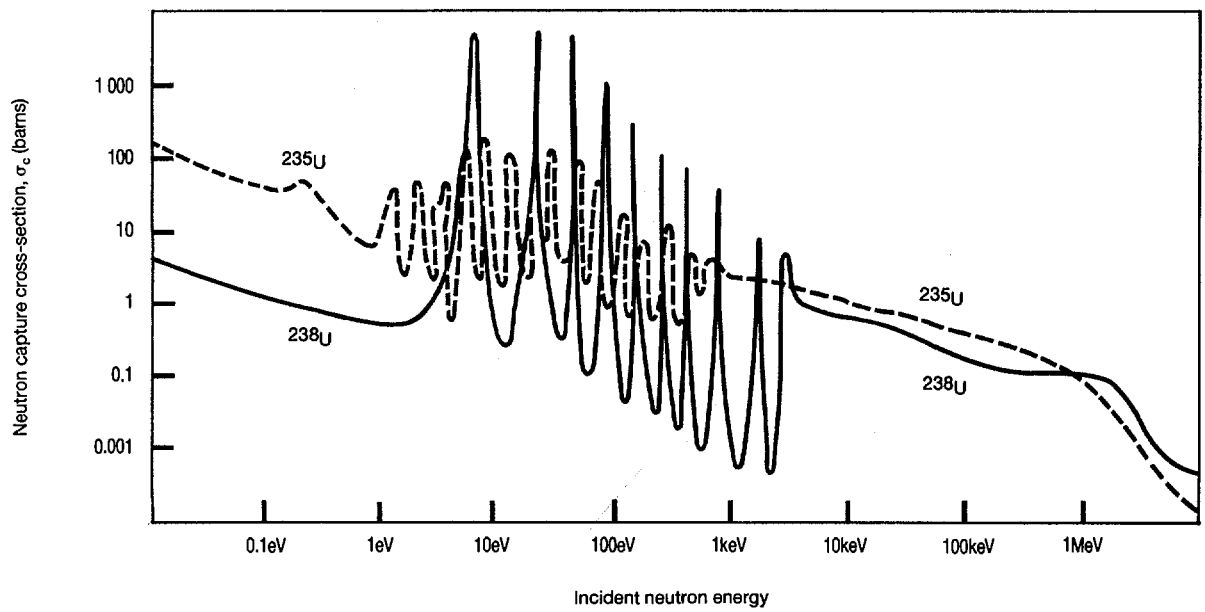


Table 1

THE PLUTONIUM COMPOSITION DEPENDENCE ON THE INITIAL CYCLE
AS PERCENTAGE OF TOTAL Pu + Am-241

(immediately after unloading)

CYCLE		Pu-236	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241/Pu + Am-241
Enrichment U_{235}/U	Burn-up GWd/t	ppm	%	%	%	%	%	ppm
3.25 %	33	12	1.26	56.62	23.18	13.86	4.73	3 500
3.70 %	43	15	1.97	52.55	24.09	14.73	6.22	4 400
4.40 %	53	20	2.74	50.37	24.15	15.16	7.06	5 100

1.4 Plutonium Radioactivity

All isotopes of plutonium undergo spontaneous decay (Table 2). Plutonium-238 has a relatively short half life and heat from its decay is used to power small electric batteries that have been used in heart pacemakers, space satellites and land based navigational beacons. Plutonium powered batteries also supported seismic and other equipment placed on the moon's surface by the Apollo mission, and the cameras that enabled the Voyager space craft to send back pictures of Saturn, Jupiter and Neptune.

Plutonium-239, the main isotope, decays with a half life of 24,390 years, emitting alpha-particles like those emitted by naturally occurring uranium and radon. The most stable isotope of plutonium is plutonium-244 with a half life of 80 million years. It is not present to any significant extent in spent uranium fuel. The other isotopes also release alpha-particles, all reverting to isotopes of uranium except for plutonium-241 which in over 99.9 per cent of its decays emits a beta-particle to produce americium-241, which decays to neptunium-237 by alpha-decay and thence to plutonium-237 which decays by electron capture.

Table 2

PLUTONIUM ISOTOPES

Isotopic Mass	Half Life	Decay Mode (a)(b)	Specific Activity 10^9 Bq/g	Spontaneous fission neutrons n/g.s.	Heat Generation mW/g	Product
236	2.8 y	α	1.9×10^4	37×10^3	-	U-232
237	45.3 d	$\beta+$	-	-	-	Np-237
238	87.7 y	α	6×10^2	2.6×10^3	560	U-234
239	2.4×10^4 y	α	2	0.03	1.9	U-235
240	6.5×10^3 y	α	8	1.0×10^3	6.8	U-236
241	14.4 y	β	3.7×10^3	-	4.2	Am-241
242	3.8×10^5 y	α	0.1	1.7×10^3	0.1	U-238
Am-241	4.3×10^2 y	α, γ	1.2×10^2	1.1	114	

a. 0.002 per cent of Pu-241 decays produce alpha-particles.

b. All the decay processes are accompanied by the emission of some X-rays or gamma-rays.

The alpha- and beta-particles are easily stopped by the thinnest of protective barriers so that external radiation is not usually a problem when recently separated plutonium from any low burn-up fuel is handled in closed glove boxes.

However, all the isotopes emit some X-rays and or gamma-rays which can pass through the rubber and perspex used in simple glove boxes. The decay products of plutonium-236, namely bismuth-212 and thallium-208, emit penetrating gamma-rays while separated plutonium containing significant quantities of plutonium-241 (for example from spent LWR fuels) begins to accumulate americium-241 on storage and this is an isotope that also emits gamma-rays.

Most plutonium isotopes also undergo spontaneous fission so that plutonium and its compounds emit neutrons both from this source and from the nuclear reactions occurring when atoms of lighter elements are bombarded by high energy alpha particles, e.g. from plutonium-238 and plutonium-240. Table 3 summarises the surface dose rates of X-rays, gamma-rays and spontaneous fission neutrons emitted from pure plutonium nuclides (13).

Table 3

SURFACE DOSE RATES FOR 1 KG SPHERES OF PURE NUCLIDES
(milliSv per hr.)

Isotope	X-Rays	γ-Rays	Spontaneous fission neutrons*	% of isotope in 33 000 MWd/t PWR fuel
Pu-238	5.7×10^3	2.4×10^2	640	1.4
Pu-239	8.9	3.2	< 0.01	57.1
Pu-240	72	0.8	300	22.0
Pu-241	-	120	-	13.7
Pu-242	1.3	-	310	5.5
Am-241	4×10^3	2.7×10^4	0.15	-

* Excludes alpha-neutron reactions which would add to doses from oxide fuels.

Whereas the alpha- and beta-radiation are only harmful when plutonium enters the body, the emissions of penetrating gamma-rays or neutrons mean that additional shielding is needed at some stages, together with the use of automation and improved maintenance techniques, to reduce radiation doses to workers. This is particularly important when plutonium from LWR fuels is used with its higher concentration of undesirable isotopes compared with plutonium from low burn-up gas-graphite reactor fuels. These techniques are already in use for handling plutonium and the much more radioactive spent fuel and high activity fission products.

1.5 The Toxicity of Plutonium

The biological effects of plutonium, when taken into the body by inhalation, ingestion or via a wound are due primarily, if not indeed exclusively, to the alpha particles emitted in the decay of the principal isotopes (plutonium-238, plutonium-239 and plutonium-240) or the daughter product of plutonium-241 (i.e. americium-241).

The metabolic behaviour of plutonium has been dealt with in detail elsewhere (1), (3), (15-19). In summary, the fate of plutonium entering the body depends on: its chemical properties; its physical size and shape if in particulate form; and the means of intake (inhalation, etc). Certain forms of plutonium, particularly very finely divided (sub-micron) plutonium dioxide, when inhaled are avidly retained by the lung and associated lymph nodes. Plutonium nitrate, on the other hand, is soluble and readily translocated from the lung to the bloodstream, thence becoming available for distribution within the various body organs. In the case of ingestion of plutonium, the amount transferred from the gut to the bloodstream is very small in all cases and can be further reduced by appropriate counter measures. Quoted fractional transfers for adults lie in the range 10^{-3} to 10^{-5} (16) dependent on the nature of the ingested material. Plutonium entering through a wound may be retained at the wound site or migrate to the bloodstream. The mechanism depends very much on the form of the contaminant.

Once in the bloodstream, the principal organs of deposition are the bone and liver which between them account for 90 per cent of the uptake and are assumed to have half lives for retention of 50 and 20 years respectively. The remaining 10 per cent is generally deposited in other organs, including the gonads, or excreted.

Inhalation is the most important route of intake, particularly for occupational exposures but ingestion can be important in considering environmental exposure and critical group doses, e.g., shellfish eaters from accidentally contaminated areas near reprocessing plants.

When plutonium has entered the body, for example as a consequence of chronic exposure to a low level of airborne activity or as a consequence of a wound caused by a contaminated object, the biological effect of principal interest is the possible initiation of cancers in the long term in a small proportion of those exposed (the stochastic mechanism). This is discussed in more detail in the following sections. Clearly, the intake of high levels of plutonium, by whatever mechanism, could result in acute, non-stochastic, effects as a consequence of a localised high dose rate. It has been suggested that acute effects may occur with body activity contents in excess of 10^5 Becquerel (one Bq corresponds to one disintegration per second) (14) and that lethal doses, for insoluble plutonium in the lung, would have an activity of the order of 10^7 Bq (15). In practice ingested plutonium is less acutely toxic than many common poisons (strychnine, lead arsenate and cyanide) and even on inhalation its acute toxicity is not very different from heavy metal vapours like cadmium and mercury. However, the levels at which acute effects might occur are many orders of magnitude in excess of the levels encountered in normal occupational exposure where body activity contents below 10^2 Bq are encountered.

The principal area of interest therefore lies in the long term stochastic effects of plutonium exposure. For radiation protection purposes and to err on the safe side such effects are assumed to be without threshold and to be associated with a linear relationship between dose and risk to the individual. Thus the greater the dose, the greater the risk: that risk being the probability for development of a cancer. The objective of good radiological protection is to maintain exposure "As Low As Reasonably Achievable" (ALARA) and below levels that present an unacceptable degree of risk so that, provided it is properly contained and handled, there are no significant biological problems in the use of plutonium.

The levels of plutonium that are regarded as acceptable in the environment (the derived limit) are calculated from the estimated effects of alpha-radiation on the tissues of the different organs of the body, taking into account the possible concentration of plutonium in the environment through physical and biological processes, such as food chains, and of its concentration within the organs of the human body. These lead to derived environmental concentrations expressed in terms of, for example, derived airborne concentrations (measured in Bq per m^3). Control of exposure within these limits results in doses to individuals being less than the relevant primary dose limit. In practice, the concept of ALARA results in actual exposures at only small fractions of the derived limit.

It is evident that for both ingestion and inhalation plutonium is at worst comparable to many other materials in terms of its acute toxicity. For plutonium entering the body in lower concentrations the principal biological effect would be cancer induction, although no cancers have occurred in man that can be attributed with confidence to plutonium, even in individuals who have, through accidents, absorbed abnormally large amounts (16).

In terms of delayed cancer induction plutonium is predicted to be little different from naturally occurring radioactive elements like radium-226, although the absorption behaviour in the body has to be taken into account and relative effects vary from organ to organ.

Empirical observation of clusters of leukemia cases in proximity to some (though not all) nuclear plants in some countries has led to the assertion that there is a positive link between low concentrations of plutonium in the environment and the disease. The observed environmental levels are regarded by health physicists as far too low for it to be the causative agent. The fact that similar clusters occur in some countries with no nuclear industry and that a systematic search in the UK has revealed much larger clusters of the same forms of leukemia in areas with no nuclear plant (20) means that different causative agents have to be sought.

Plutonium is far from being the uniquely hazardous material of popular imagination. Rather it is one amongst many toxic materials that have to be handled with due caution to minimise the associated but well understood risks.

1.6 Plutonium Fission

1.6.1 The Fission Process

Atoms of plutonium undergo fission (i.e. split apart) and release energy when bombarded with either thermal or fast neutrons, in the same way as atoms of uranium-235 and uranium-233. Atoms with nuclei having odd nuclear masses (e.g. 239, 241) fission much more readily than the even-mass isotopes (238, 240, 242) and this difference is particularly pronounced for thermal neutron fluxes. The fission process produces atoms with smaller nuclei (fission products) plus a number of fission neutrons which can go on to produce further fissions in other fissionable nuclei (21).

The number of neutrons produced per fission depends on the energy of the incident neutron and the fissionable isotope involved (Figure 4, from ref. 11). At low (thermal) energies around 2.5 neutrons are produced per fission, whereas with a fast neutron spectrum with energies above 100 keV the number rises, particularly for plutonium-239 (Figure 4) with a typical yield of 3 neutrons per fission.

Some of the incident neutrons will inevitably be captured in the fissile isotopes without inducing fission (Figure 3) so that the average number of neutrons produced per neutron absorbed is less than the yield per fission (Figure 5): around 2 neutrons per incident neutron at low energies, rising to 2.6, typically for plutonium-239 in fast neutron fluxes. If this neutron yield per fission event (Ψ) exceeds by one the sum of the number of neutrons (L per fission event) parasitically captured in the

moderator, structural materials or any fission products, together with any that are otherwise lost to the system, plus the number (B per fission event) captured in the fuel to produce new fissile atoms, then a self sustaining or chain reaction can occur and the fuel mass is said to be critical.

$$\Psi = B + L + 1$$

A nuclear reactor core has to contain enough fissile material to be capable of becoming critical so that it can produce energy continuously. Control is effected by inserting or withdrawing neutron absorbing control rods which can increase or decrease L depending on whether it is desired to shut down the reactor or increase the rate of energy output (21).

The excess of neutrons, B per fission, over the number needed to compensate for losses and sustain the fission chain reaction (L+1), is available to produce fresh fuel atoms.

$$B = \Psi - L - 1$$

In thermal reactors using uranium-235 as fuel the excess (B) is around 0.5 and these neutrons do change fertile uranium-238 in the fuel to fissile plutonium-239, some of which is burnt *in situ* and some of which remains in the spent fuel and can be extracted and used in other reactors.

Where B is less than unity the reactor acts as a converter and produces less fissile material than it consumes.

In fast neutron reactors the higher yield of fission neutrons and absence of a moderator allows B to reach levels of around 1.2 to 1.3 so that more fuel can be produced than is consumed, i.e. they breed.

Figure 4. **AVERAGE NUMBER OF NEUTRONS RELEASED FROM FISSION**

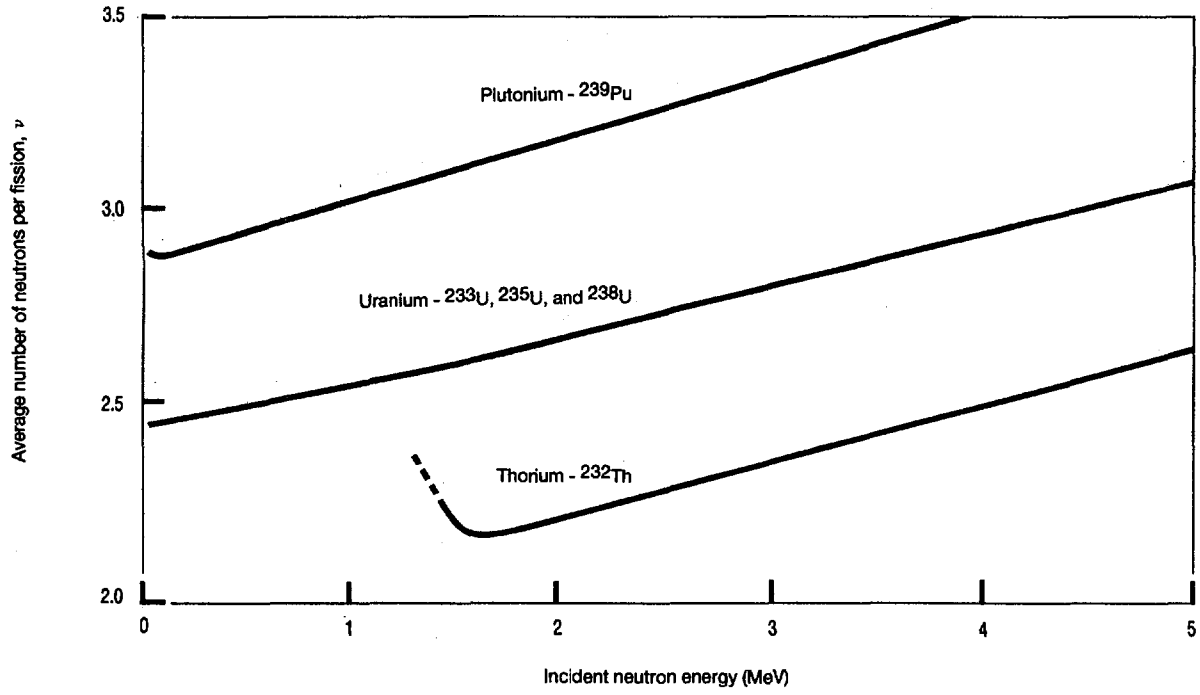
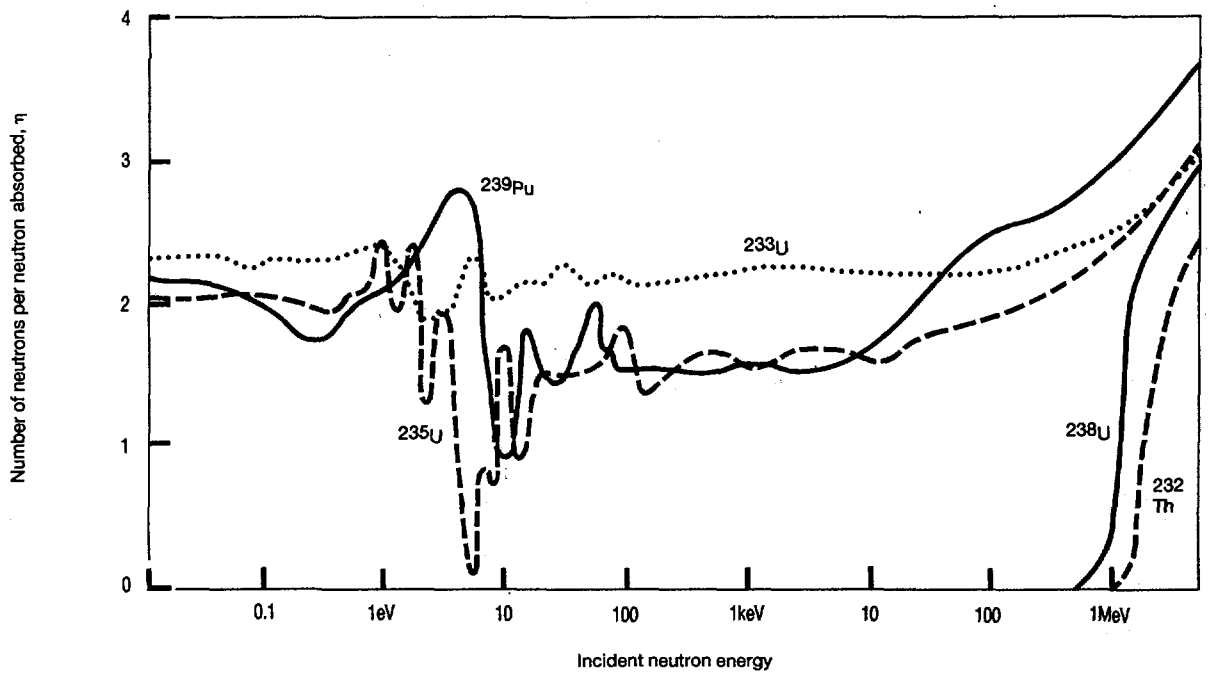


Figure 5. **NEUTRON YIELD PER NEUTRON ABSORBED**



This is an extremely important property since it opens up the opportunity of progressively converting the world's resources of non-fissile uranium-238 into nuclear fuel and increases the energy recoverable from uranium by a factor of 50-100 after allowance for processing losses. (Thorium-232 is also fertile and can be converted to fissile uranium-233 in the same way).

1.6.2 Plutonium Fissionability

As described in Section 1.3, the isotopic composition of the plutoniumm produced in reactors differs depending on a number of factors (see Table 4 from ref. 22).

Isotopes behave differently in terms of their ability to fission at different neutron energies and in the number of neutrons emitted per fission (Figures 3 and 4). Thus uranium-235 is fissionable by both fast and thermal neutrons whereas uranium-238 is essentially a neutron absorber which undergoes some fission at high neutron energies.

The number of neutrons released per neutron absorbed by a fissile nucleus (η) is related to the number of neutrons released per fission (Ψ) by:

$$\eta = \Psi \ \sigma_f/(\sigma_f + \sigma_c)$$

where σ_f and σ_c are the fission and capture cross sections for the nucleus at the particular range of incident neutron energies. (The cross section is a measure of the likelihood that a fission or capture event will occur).

Table 4

AVERAGE ISOTOPIC COMPOSITION OF PLUTONIUM
PRODUCED IN URANIUM-FUELLED THERMAL REACTORS

Reactor Type	Meanfuel burn-up (MWd/t)	Percentage of Pu isotopes at Discharge				
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Magnox	3 000	0.1	80.0	16.9	2.7	0.3
	5 000	*	68.5	25.0	5.3	1.2
CANDU	7 500	*	66.6	26.6	5.3	1.5
AGR	18 000	0.6	53.7	30.8	9.9	5.0
BWR	27 500	2.6	59.8	23.7	10.6	3.3
	30 400	*	56.8	23.8	14.3	5.1
PWR	33 000	1.3	56.6	23.2	13.9	4.7
	43 000	2.0	52.5	24.1	14.7	6.2
	53 000	2.7	50.4	24.1	15.2	7.1

* Information not available.

The larger η the smaller the amount of the fissile isotope needed in the fuel to reach criticality, and for a given level of core reactivity, the amounts of alternative fissile materials needed will be in inverse proportion to their η values.

Of the plutonium isotopes, only plutonium-239 and plutonium-241 are fissile in a thermal neutron flux; plutonium-238 and plutonium-240 are fertile, yielding plutonium-239 and plutonium-241 through neutron capture; and plutonium-236 and plutonium-242 are neutron absorbers.

It is therefore possible to replace fissile uranium-235 with fissile plutonium isotopes (plutonium-239 and plutonium-241) in a thermal reactor. The amount of fissile plutonium required to substitute for a given amount of uranium-235 to produce the same amount of energy would depend not only on the differences in neutronic characteristics (such as σ), but also on the amount of fissile plutonium loaded and its spatial distribution within the fuel assembly and the core (fuel management).

In a typical light-water reactor environment, the replacement ratio between fissile plutonium and uranium-235 is approximately 1.3 to 1.0 *on an atom-to-atom basis*; that is 1.3 fissile plutonium atoms are required to replace one atom of uranium-235. This results from the need to increase the fissile loading of the plutonium fuel to compensate for a large absorption of lower energy neutrons by plutonium-240 (at about 1.05 eV), despite plutonium's higher neutron yield (average number of neutrons emitted per neutron absorbed in fuel: 2.06 for uranium-235 vs. 2.10 for plutonium-239 in a thermal neutron spectrum). The contributions of the different isotopes are shown in Table 5 and Annex G contains further explanation of the energy "equivalence" concept.

Table 5

PLUTONIUM EQUIVALENT WORTHS IN LWRs AND FBRs

Pu-239 = 1.00

ISOTOPE	LWR	PHENIX (250 MWe)	SUPER-PHENIX (1200 MWe)	SUPER-PHENIX 2 (1500 MWe)
U-235	+ 0.8	+ 0.71	+ 0.77	+ 0.78
U-238	0.0	0.0	0.0	0.0
Pu-238	- 1.0	+ 0.49	+ 0.44	+ 0.43
Pu-239	+ 1.0	+ 1.0	+ 1.0	+ 1.0
Pu-240	- 0.4	+ 0.20	+ 0.14	+ 0.13
Pu-241	+ 1.3	+ 1.40	+ 1.50	+ 1.52
Pu-242	- 1.4	+ 0.086	+ 0.037	+ 0.026
Am-241	- 2.2	- 0.23	- 0.33	- 0.35

This table provides an illustration of the energetic value of the main uranium and plutonium isotopes (and americium-241) in comparison to the plutonium-239 isotope (atom per atom) in LWRs and three different generations of French FBRs. For further explanation, see Annex G.

In practice the combined amount of uranium-235 plus fissile plutonium loaded into mixed oxide fuel should be anywhere between 5 and 10 per cent greater than the amount of uranium-235 loaded into uranium oxide fuel *on a batch average basis.* (Note that only a fraction of fuel assemblies in a given batch may contain plutonium).

In a fast neutron flux the equivalent energy worths are expressed relative to plutonium-239 and are quite different as indicated in Table 5 which is based on French data for the neutron spectra in their fast reactor designs.

Care has to be taken in referring to quantities of plutonium since they can be quoted in terms of total plutonium (Pu_t), which is the mass of all isotopes present; in terms of fissile plutonium (Pu_f), which is the mass of fissionable isotopes (plutonium-239, plutonium-241) present; or as plutonium-equivalent worth (Pu_{eq}) which is a measure of the mass of plutonium-239 with the same reactivity lifetime characteristics as the sample in question (Annex G).

PART 2

UTILISATION AND NON-UTILISATION OPTIONS: THEIR LOGISTICS AND ECONOMICS

2.1 Preamble

In this part of the report the alternative ways in which plutonium can be used are summarised and the costs of the various stages of the uranium and MOX fuel cycles are discussed. The overall economics of the alternatives are then considered and set against those of options where the plutonium is not recycled. In order to do this the pre- and post-irradiation compositions of a range of fuels have been calculated for a number of alternative fuel strategies.

2.2 Utilisation and Non-Utilisation Options

There is in principle a wide range of choices open to the nuclear plant operator concerning his treatment of the plutonium produced in thermal reactor fuel.

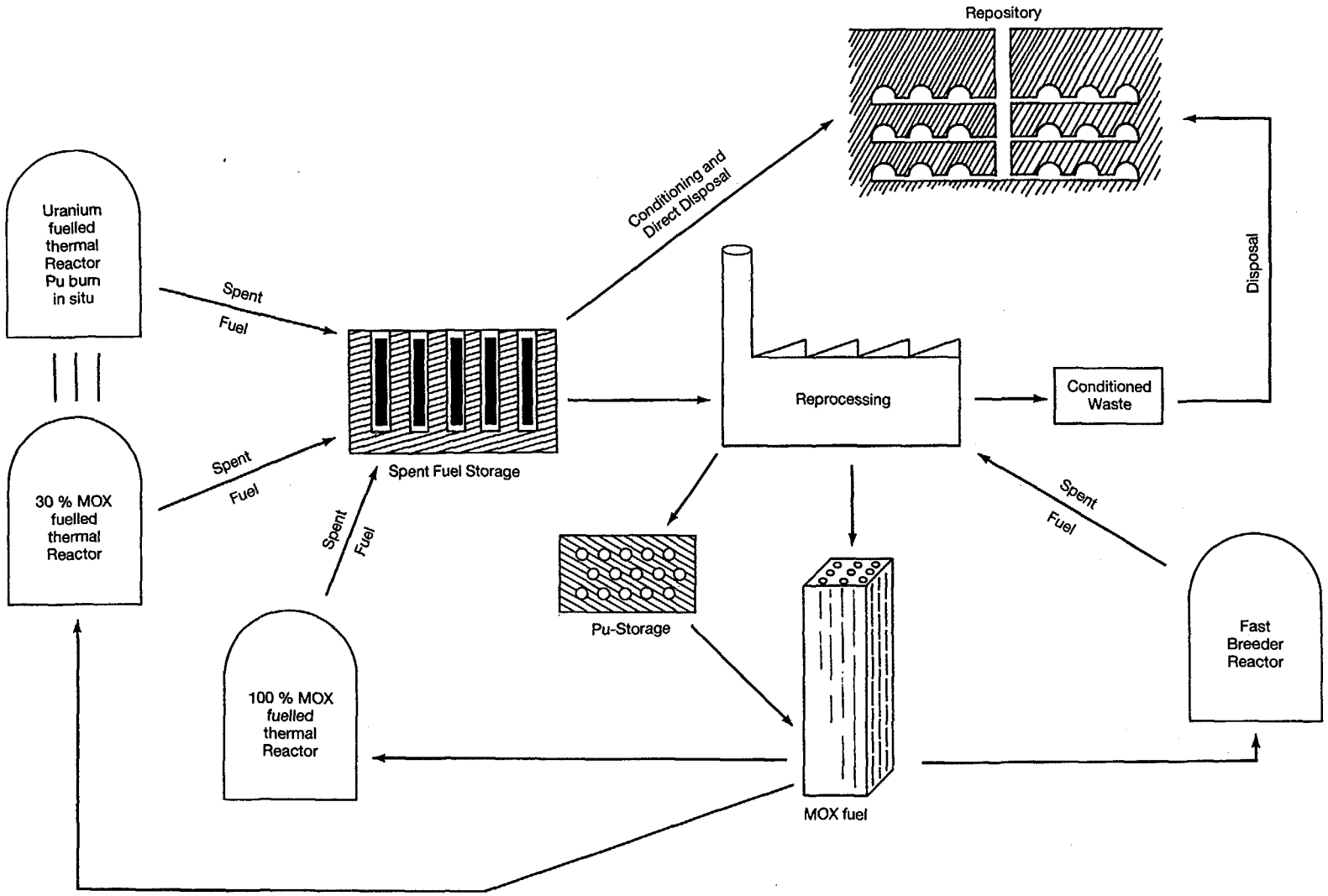
Most uranium fuelled thermal reactors derive some of their energy from the in situ consumption of fissile plutonium produced by neutron capture in the uranium-238 of the feed fuel. It is not always appreciated that light water reactors with discharge fuel burn-up of around 33 000 MWd per tonne on average derive some 30 per cent of their energy output from this source. Moving to higher fuel burn-up in the reactor would increase the quantity of energy recovered from plutonium in situ and produces somewhat more fissile plutonium though the Pu_f/Pu_t ratio is lower (see Table 9). In effect therefore an important first option concerning plutonium use is the choice of initial uranium fuel composition and its burn-up.

The second fundamental decision is whether spent uranium fuel is to be reprocessed to recover plutonium and unused uranium or not. Unprocessed fuel has to be stored and ultimately disposed of, although at any time prior to ultimate disposal the option of reprocessing can be taken up.

If fuel is to be reprocessed there is the question of when this should take place. This depends on the intended use of the recovered plutonium and uranium, and on technical, environmental, operational and economic factors which are discussed in Section 2.3.

The recovered plutonium can be used in either thermal or fast reactors. Its use in thermal reactors affects but does not preclude its subsequent use in fast reactors (Section 2.4.6) although it has a higher energy worth and can be used more effectively in the latter. In thermal reactors it can be used in a self-generated mode, where plutonium is recycled only in the reactor producing it, or in the non-self generated mode where plutonium from several reactors can be used to fuel one or more mixed oxide fuelled reactors. The full range of options is illustrated in Figure 6.

Figure 6. **PLUTONIUM RECYCLING OPTIONS***



* Reprocessed uranium can either be recycled directly in MOX fuel or it can be reenriched and then recycled together with fresh enriched natural uranium.

There are however additional choices beyond those so far described:

(a) Mixed oxide fuel can be produced with uranium dioxide made from fresh natural uranium, with uranium dioxide made from enrichment plant tailings (depleted in U-235), or with uranium recovered by reprocessing spent fuel (slightly enriched residues from LWR fuel or slightly depleted from reactors fuelled with natural uranium).

(b) Plutonium could be used in existing or specially designed thermal reactors. The neutronic properties of the mixed oxide fuel will differ from that of uranium oxide and this can affect the physics of the reactor and its control. For this reason the proportion of MOX fuel will be limited to about 30 per cent of the total fuel when it is used in existing PWRs in order to maintain adequate power distribution and shut down margins (23). This proportion limit can be increased by installing additional control rods in the reactor or by incorporating adequate burnable absorbers in the fuel assemblies (26) or by combining both. Future PWRs could be redesigned specifically to use plutonium and then could be wholly MOX fuelled. Such a course could have economic advantages in terms of minimising the special costs associated with plutonium fuel transportation, storage and use. However, the numbers of such reactors will always be less than the extra number of standard PWRs (see Section 2.4.5) and the extra design and engineering costs might not be attractive or merited.

(c) A MOX fuelled thermal reactor could operate on a reprocessing cycle (provided sufficient reprocessing capacity exists for MOX) or in a once-through mode with the spent MOX fuel stored pending decisions on later use. In the former case the quality and fissile worth of the plutonium decreases with repeated thermal recycle and this imposes a limit on what can usefully be done. Mixing fresh and multiply recycled plutonium in new fuel can reduce the problem, or possibly eliminate it (24). MOX fuel has been and is being reprocessed without difficulty in suitably designed plants.

It will be evident from the foregoing that the options displayed in Figure 6 contain a large number of variants which can have significant technical, economic and logistic impacts. Apart from the choice of MOX fuelled reactor type and its design optimisation, these variants include different uranium fuel burn-ups, different spent fuel storage times prior to reprocessing and plutonium storage times prior to MOX fabrication. They include different sources of uranium fuel and different MOX fuel compositions as well as different policies towards recycling MOX itself.

The options explored in detail in this study have been limited to a range of MOX fuels designed for different burn-ups for use in existing PWRs which were initially uranium fuelled. The PWR is the most widely used reactor and MOX is already loaded in a significant number of PWRs. The use of MOX fuel has also been demonstrated in BWRs and is further contemplated for the near future. PWRs and BWRs are the only cases of wide relevance in the 1990s. The fast reactor and the redesigned wholly MOX fuelled PWR (if the latter is developed) will not be deployed on a significant scale until the next century. No consideration is given to the Japanese MOX fuelled Advanced Thermal Reactor which was covered in an earlier report (4) or to thorium cycles which are not being actively developed in OECD countries, or to the use in CANDU of uranium and plutonium recovered from discharged LWR fuel.

For the medium term at least it also looks unlikely that MOX fuel will be reprocessed extensively for repeated recycle of plutonium in PWRs, not least because of the lead times involved. The difference in energy worth of plutonium between thermal and fast reactors is greater for multiply recycled material, and this may also influence fuel plans in some countries. For this reason detailed consideration is only given to the once-through mode of MOX fuelling with mention of the economic implications of multiple recycle where appropriate.

The interactions and trade-offs between these and other variants are explored in the succeeding sections of this report.

2.3 Technical Factors Affecting Decisions on Plutonium Recovery and Use

2.3.1 The factors considered

The main technical factors that determine national or utility policies concerning the act and timing of plutonium separation arise from the long term integrity of the cladding and consequent storability of existing reactor fuels, preferences in connection with radioactive waste management, the usability of recovered uranium, and the effect of separation or storage of plutonium on its composition and properties.

Plutonium isotopic composition, which depends on uranium fuel burn-up, can affect its physical handling and will alter its energy worth, both of which can have an impact on costs, while safety considerations impose constraints on the way it can be used.

The decisions on its use are conditioned by political, economic and strategic factors as well as by technical considerations. The non-technical factors, including the value attached to recovered uranium, are dealt with in later sections.

2.3.2 Storage Limitations for Spent Thermal Fuel

Zirconium alloy cladding has been adopted because of its low neutron absorption and also for other reasons, e.g. in LWRs to keep waterside corrosion at acceptable levels. Zircaloy cladding is well able to withstand prolonged periods (many decades) of storage in water filled cooling ponds provided the water quality is carefully maintained. There is no short-term safety or environmental incentive therefore to reprocess such fuel.

Some fuels however have been encased in other materials such as Magnox alloy, stainless steel or graphite coatings whose characteristics are matched to other types of thermal reactor. They therefore may not be suited to long term wet storage and may require early reprocessing. British Magnox and French gas graphite reactor fuels are in this category (see Annex A).

2.3.3 Fuel Burn-Up and Plutonium Quality

The extent of fuel burn-up determines the amount of recoverable plutonium but also affects the isotopic composition of the plutonium in spent fuel, which in turn can affect the ease of utilisation and value of plutonium when it is recycled (see also Section 2.7.4).

The presence of plutonium-238, which produces significant quantities of heat (and neutrons from alpha-neutron reactions), is a factor which has to be considered in the design of transport and storage equipment for plutonium and mixed oxides. This isotope is present in somewhat higher quantities in high burn-up fuel (Table 1).

Another effect of importance is the neutron absorption of the isotopes in the fuel. The concentration of the absorbing isotopes plutonium-240 and plutonium-242 increases with burn-up (Table 1) and this demands a higher initial fissile isotope content in MOX fuel made with plutonium from high burn-up LWR fuel. The odd numbered isotopes produced by neutron capture are fissile however and contribute to subsequent energy production.

2.3.4 Timing of Reprocessing and Plutonium Quality

When fuel is removed from a reactor fresh plutonium production ceases immediately and radioactive decay becomes the dominant feature. The half-life of plutonium-239 is sufficiently long that it remains effectively unchanged. The shorter lived isotopes decay and fissile plutonium-241 is replaced by neutron absorbing americium-241 which, together with the decay products from plutonium-236 (see Section 1.4), adds to the gamma-emission from the isotopic mixture.

This radioactive decay has two important consequences. Firstly the fissile worth of the plutonium in the thermal reactor fuel decreases with the passage of time. That is to say its usefulness as a substitute for uranium-235 in either thermal or fast reactors decreases. The rate of decrease depends only on the isotopic composition of the plutonium on removal from the reactor which was determined by the initial composition and irradiation history of the fuel itself (Section 1.3). Plutonium from fuel with higher initial concentrations of plutonium-241, such as that from high burn-up LWR fuel, will lose value more rapidly than plutonium from lightly irradiated magnox fuel with a lower initial plutonium-241 content. Figure 7 provides a quantitative view of this plutonium degradation for three reactor types and Table 6 (24) for LWR fuel. The Pu value decreases even faster as these data suggest, since the value of Pu as a fuel must be expressed in "equivalent Pu" (see Annex G).

Even more important is the fact that separated stored plutonium becomes progressively more difficult to handle as time passes, due to the growth of americium-241 and the high energy gamma-emitting decay products derived from plutonium-236. A short interval between reprocessing and plutonium fuel fabrication is to be preferred.

Both the fissile worth (marginally) and the high energy gamma-emission from the plutonium (significantly) can be modified by deferring reprocessing and plutonium separation until the latter is wanted for use in fuel. Table 7 (12) shows how deferred reprocessing affects the americium levels. If the fuel were reprocessed promptly and the plutonium stored separately, the americium levels would correspond to the much higher "before reprocessing figures". The situation for Magnox and oxide fuels is shown in Figure 8.

Figure 7. **DECAY OF FISSILE PLUTONIUM WITH TIME**

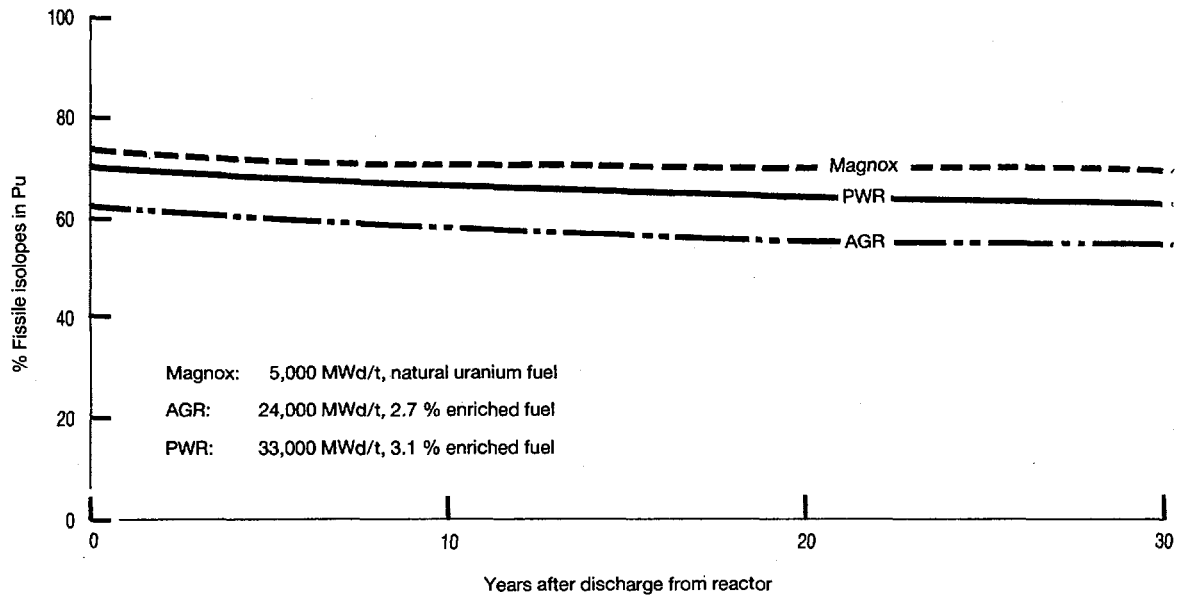


Table 6

CHANGE WITH TIME OF ISOTOPIC CONCENTRATION OF PLUTONIUM FROM LIGHT WATER FUEL REACTOR

Years after unloading	Pu composition (per cent)						
	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Pu-tot	Am-241
0	1.26	56.62	23.18	13.86	4.73	99.65	0.35
2	1.26	56.62	23.18	12.44	4.73	98.23	1.77
5	1.26	56.62	23.18	10.52	4.73	96.31	3.69
10	1.26	56.62	23.18	8.28	4.73	94.07	5.93
15	1.26	56.62	23.18	5.69	4.73	91.48	8.52

Source: Ref. 24, recalculated to match data in Table 9 of this report.

Figure 8. **BUILD UP OF AMERICIUM IN PLUTONIUM WITH TIME**

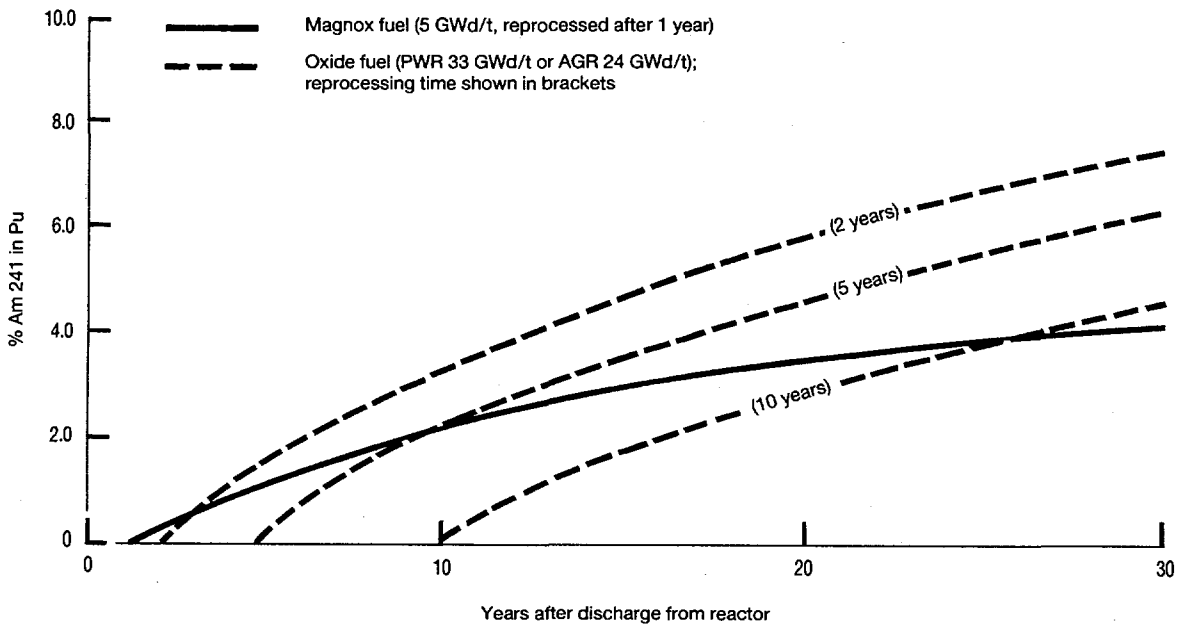


Table 7

AMERICIUM-241 CONTENT IN THE FUEL
AT DIFFERENT STAGES AFTER UNLOADING

Am-241 content in ppm/Total Pu \ Initial Enrichment U-235/U		3.25 %	3.70 %	4.40 %
Unloading		3 500	4 400	5 100
Reprocessing after 3 years	Before reprocessing	24 600	26 800	28 000
	2 years after reprocessing	10 800	11 200	11 600
Reprocessing after 5 years	Before reprocessing	36 900	39 900	41 600
	2 years after reprocessing	9 980	10 300	10 670
Reprocessing after 10 years	Before reprocessing	59 300	63 700	66 610
	2 years after reprocessing	8 100	8 400	8 700

Source: Ref. 12, recalculated to match data in Tables 9 and 12 of this report.

At the present time some countries have large stocks of unreprocessed fuel while a few have stocks of separated plutonium, some of which has been in store for a long time. The latter countries also continue to separate plutonium from spent fuel after a cooling period ranging from 2 to 10 years. In general, preference will be given to using freshly separated plutonium for MOX production and it is expected that oxide fuel storage periods prior to reprocessing will decrease during the 1990s. Control of both factors will be possible in the future with careful management of buffer stores of spent fuel, separated plutonium (as dioxide) and MOX, sized to minimise the costs of the fuel cycle.

It is always possible to subject separated stored plutonium to a further chemical purification stage to remove americium and other contaminants before fuel is manufactured, but this represents an additional cost which can be avoided by deferring the initial reprocessing of the fuel.

The presence of the gamma-emitting isotopes does not preclude the use of the degraded plutonium in fuel, but it would demand automation and higher levels of shielding during fabrication and handling

of the fresh mixed oxide fuel prepared using it than are needed for alpha-emitting natural or enriched uranium fuels. This would add to the expense and inconvenience, but it is technically feasible. The techniques for handling and transporting high energy gamma-emitting fission products have already been established for spent fuel transport and reprocessing. Costs could decrease in future as throughputs increase partly as a result of automation. On the basis of practical experience some indicative limits have been derived which show roughly how long plutonium containing materials can be stored before use without running into significant difficulties. These "rough limits" are set out in Table 8 (25). They are not absolute but reflect the current state of technology, which can accommodate americium levels of about 1 per cent without incurring extra costs.

Table 8

INDICATIVE LIMITS FOR PLUTONIUM STORAGE SINCE PLUTONIUM PURIFICATION*

Plutonium-Bearing Material	Maximum Storage Period
PuO_2 powders	2 years
MOX fuel rods	10 to 13 years
Fresh MOX fuel assembly	13 to 20 years
Spent MOX fuel assembly	unlimited

* PWR plutonium.

Clearly there are complex trade-offs between the period and costs of storage of fuel, separated plutonium and MOX and the costs of the processing, handling and fabrication stages of the fuel cycle to which we will return in later sections of this study.

2.3.5 Reactor Control

A technical factor of major importance is the difference in the neutron absorption and emission of plutonium compared with that from uranium-235. Plutonium has a much higher neutron absorption, it emits fewer delayed neutrons and shows considerable variation in fission neutron yield with incident neutron energy when the incident energies are low. These characteristics reduce the effectiveness of the conventional control systems in a LWR optimised for uranium oxide fuel. Detailed studies sponsored by the Commission of the European Communities (23) amongst others show that such reactors can take up to about 30 per cent of their fuel in the form of mixed oxide without necessitating any design modifications.

Nevertheless it is not possible to adopt a single mixed oxide fuel composition for use throughout the reactor core and variable plutonium oxide contents are needed in different regions of MOX fuel assemblies in order that the overall core can be managed so that its neutron flux distribution resembles that in a wholly uranium oxide fuelled core (see Annex B).

The different neutronic behaviour of plutonium also calls for a full safety analysis to ensure that the reactor remains within its safety envelope derived for uranium fuel.

A PWR or other reactor that has its control and safety systems optimised for use solely with mixed oxide fuels is an alternative option. For the reasons given in Section 2.2 this option is not considered in detail here. A limited number of such reactors could be supported within a thermal reactor network (Section 2.4.5).

The use of mixed oxide assemblies should not modify the flexibility and in particular the load following of LWRs compared with uranium fuelled plants. Several studies are being undertaken in order to take into account the specific design features of the assemblies and the reactor operating conditions, and no difficulties are foreseen, although some minor modifications to equipment may be necessary (12).

2.4 The Logistics of Plutonium Recycle

2.4.1 General

This section is concerned with the quantitative aspects of plutonium production and consumption in individual reactors.

Quantities in the text are referred to in rounded terms since their precise values depend on a number of factors which are described in the following paragraphs. Computer simulation models for specific reactors operating under carefully defined conditions are required if the changing isotopic composition of MOX fuels is to be predicted with confidence. Running such models is a necessary precurser to a detailed examination of the consumption of plutonium and the economics of MOX fuels. Calculations of this type have been undertaken for the cases selected for detailed consideration in this study. These are described in appropriate sections and relate to the specific PWR defined at Annex C.

2.4.2 Plutonium Production in Uranium Fuelled Thermal Reactors

For a pressurised water reactor 6.1 t of natural uranium are required to produce 1 t of fuel enriched to 3.25 per cent in uranium-235 with O.2 per cent uranium-235 enrichment tails. At 33 000 MWd per tonne burn-up, when an equilibrium batch of fuel is removed from the reactor, it contains a residual 0.9 per cent uranium-235, 0.95 per cent plutonium (total) and 3.3 percent fission products and other transuranic elements (Table 9). About 3 per cent of the uranium atoms in the fuel have been fissioned but only 2.3 per cent through direct fission of uranium-235 atoms. The remaining 0.7 per cent have been converted via in situ production and fission of plutonium. The precise composition of fresh and spent fuel batches depends on the reactor and its operation.

The yields of plutonium depend not only on reactor type and design but also on the fuel burn-up and the neutron flux. Typical yields for different PWR fuels and burn-up are given in Table 9 and for other reactor types (on an indicative basis only) in Table 10.

2.4.3 Uranium Savings from Uranium Recycle

The uranium removed from spent 33 000 MWd per tonne PWR fuel contains about 0.9 per cent of uranium-235 compared with an initial enrichment of 3.25 per cent and a concentration in natural uranium of 0.7 per cent. At prevailing prices re-enrichment can recover economically about 75 per cent of the fissile isotope for recycle and in the absence of complicating factors this would add 20 per cent (75 per cent of 0.9/3.25) to the energy recoverable from the initial uranium and 4 per cent (20 per cent of 20 per cent) for a second recycle.

Table 9

PWR URANIUM FUEL

ISOTOPIC BALANCE FOR ONE TONNE OF FUEL

(as weight per tonne in [kg] and as percentage [%] of total U for uranium and of total Pu + Am for plutonium and for americium)

FUEL SPECIFICATION / ISOTOPE:	U-235		U-236		U-238		U-tot	Pu-238		Pu-239		Pu-240		Pu-241		Pu-242		Am-241		Pu-tot*	Pu/Pu + U**
UNIT:	kg	%	kg	%	kg	%	kg	kg	%	kg	%	kg	%	kg	%	kg	%	kg	%	kg	%
3.25 % U-235+	32.5	3.25	0.0	0.0	967.5	96.75	1000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33 000 MWd/t++	8.84	0.92	3.91	0.41	943.72	98.67	956.47	0.12	1.26	5.4	56.62	2.21	23.18	1.32	13.86	0.45	4.73	0.03	0.35	9.54	0.99
3.70 % U-235+	37.0	3.70	0.0	0.0	963.0	96.3	1000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43 000 MWd/t++	7.6	0.8	4.81	0.51	932.5	98.69	944.91	0.21	1.97	5.72	52.55	2.62	24.09	1.6	14.73	0.68	6.22	0.05	0.44	10.89	1.14
4.40 % U-235+	44.0	4.4	0.0	0.0	956	95.6	1000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53 000 MWd/t++	7.68	0.82	5.94	0.64	919.83	98.54	933.44	0.33	2.74	6.07	50.37	2.91	24.15	1.83	15.16	0.85	7.06	0.06	0.51	12.05	1.27

* Pu total + Am.
** Pu total + Am/Pu total + Am + U total.

\+ Before irradiation.
++ After irradiation.

Table 10

NEA "YELLOW BOOK" ESTIMATES OF FISSILE PLUTONIUM ARISINGS FROM 1 GW (NET) REACTOR OPERATING FOR 30 YEARS AT 70 % LOAD FACTOR

	Conversion ratios (B)	Pu_f (tonnes)
Unimproved PWR	0.5	4.9
Unimproved BWR	0.5	5.6
5 % improved PWR	0.56	3.8
AGR	0.5	2.9
Gas-graphite (Magnox)	0.86	14.0
CANDU	0.78	10.0
FBR	1.33	3.5

Source: Ref. 1, Table 8.7

The recovery efficiencies for the different stages in the fuel cycle are conservatively taken to be 99.5 per cent for conversion, 99 per cent for uranium and MOX fuel fabrication, and 98 per cent for the reprocessing stage of uranium or MOX fuels, following the previous economic study (4). Scrap recovery can improve on these figures (1). The uranium savings achievable by recycle of recovered uranium in LWRs are reduced by the presence of neutron absorbing uranium-236 which will concentrate in the enriched light isotope fraction and which will necessitate the use of higher uranium-235 concentrations to compensate (see Annex H, ref. 1 and ref. 26 and Section 2.5.4.4 for cost implications). The availability of highly selective laser enrichment in the future may overcome the U-236 problem.

2.4.4 Uranium Savings from Plutonium Recycle

The plutonium in spent fuel from thermal reactors differs depending on the reactor, its fuel, fuel burn-up, etc. (Tables 1, 4 and 9) and its composition will also differ as a result of the duration of subsequent storage as fuel or separated plutonium and whether or not it has been processed after storage to remove americium.

For the PWR the plutonium yield from 33 000 MWd per tonne fuel will be about 0.95 per cent by weight or 20 per cent of the total uranium consumed in the fission process. Of this plutonium some 70 per cent (Table 9) will be plutonium-239 and plutonium-241 which are fissile in a thermal reactor, i.e. about 20 per cent (0.7 x 0.95 per cent/3.25 per cent initial U-235) of the feed uranium could be replaced on a first cycle allowing for processing and fabrication recovery efficiencies.

The isotopic content of the plutonium will be degraded on subsequent recycle due to the presence of increasing proportions of the higher isotopes (Section 1.3). This will lead to a requirement for higher total plutonium concentrations in the mixed oxide fuel and the subsequent recovery of successively less fissile plutonium from the fuel batches if they are reprocessed separately from other fuel (Table 11).

Table 11

LEADING FUEL CYCLE DETAILS FOR Pu RECYCLE BWR[a] and PWR[b]

	First reload	Second reload (first recycle)	Third reload (second recycle)	Fourth reload (third recycle)	Fifth reload (fourth recycle)	Sixth reload (fifth recycle)
BWR feed						
% U-235[c] in UO_2	2.60	2.60	2.60	2.60		
% Pu[d] in MOX	-	3.44	4.05	4.61		
% MOX	nil	27.9	36.8	39.7		
Discharged Pu composition %:						
Pu-238	2.6	2.5	3.1	3.7[e]		
Pu-239	59.8	51.4	46.4	42.8		
Pu-240	23.7	25.7	26.2	26.6		
Pu-241	10.6	14.0	15.3	16.3		
Pu-242	3.3	6.4	9.0	10.6		
PWR feeds						
% U-235[c] in UO_2	3.0	3.0	3.0	3.0	3.0	3.0
% Pu[d] in MOX	-	4.72	5.83	6.89	7.51	8.05
% MOX	nil	18.4	23.4	26.5	27.8	28.8
Discharged Pu composition %:						
Pu-239	56.8	49.7	44.6	42.1	40.9	40.0[e]
Pu-240	23.8	27.0	38.7	29.4	29.6	29.8
Pu-241	14.3	16.2	17.2	17.4	17.4	17.3
Pu-242	5.1	7.1	9.5	11.1	12.1	12.9

a. Self-generation reactor recycling plutonium from 1.15 reactors.
b. Self-generation reactor recycling plutonium from itself only.
c. Based on total U only.
d. Based on total natural U + Pu.
e. Equilibrium attained.

Source: ref. 22.

NB: These calculations are based on blends of 1st generation and 2nd generation Pu in the second recycle, and so on for the successive recycles. It is therefore representative of a MOX fuel reprocessing policy by dilution, as currently proposed by the industrial reprocessors.

Overall successive plutonium recycle in thermal reactors can theoretically increase the energy recovered from the initial uranium by up to about 25 per cent, but there is general agreement that this is not a worthwhile uranium conservation measure.

2.4.5 Modes of Use in Thermal Reactors

Since the quantity of plutonium produced in conventional thermal reactors is generally less than the quantity of uranium-235 needed to fuel them, the recycling of uranium and plutonium in them can only add a limited amount to the total energy output from a given natural uranium feed.

In the case where a reactor only has access to its own self generated plutonium, it can build up to about 30 per cent MOX fuel loading (Table 11). The time taken to reach self generating equilibrium is lengthy however, firstly because the rate of plutonium production is inherently slow, secondly because the fuel is in the reactor core for some 3 years (and even more in the future) before transfer to a cooling pond where it may remain for a further 3-5 years (and currently even more) before it is reprocessed. Plutonium from the initial fuel may not therefore be available before the third reload. For this reason some 25 years are needed for single recycling reactor operating in self generating mode to reach equilibrium. When it does uranium input requirements are only about 61 per cent of those of the once-through PWR. This is academic however since it would not be economically or logistically sensible to operate reactors in this fashion.

A 1000 MWe PWR at equilibrium will consume 167 tonnes of natural uranium (24 tonnes of enriched fuel) p.a. and produce 0.115 tonnes of equivalent plutonium (thermal flux equivalent, see Sections 1.6.2 and 2.4.4). The feed required for a similar wholly mixed oxide fuelled reactor at equilibrium per year is 0.65 tonnes of fissile Pu (if it is mixed with depleted uranium feed), so that if it is operated in a once-through mode (i.e. the MOX fuel is not reprocessed), some 5 to 6 uranium fuelled PWRs will be needed to provide its fuel (Figure 9). All quantities are based on calculations for the reference 900 MWe PWR defined earlier (Annex C).

In practice the MOX loading in existing PWRs would be limited to 30 per cent so that the ratio of reactors with some MOX fuel to the total number of reactors would be far higher in practice: around 50 per cent if MOX fuelled reactors are used in the once-through mode. It would be possible, of course, to operate all reactors with MOX in the latter case by using a larger proportion of uranium fuel in each reactor (i.e. less than 30 per cent of the fuel in the form of MOX).

If the fuel from the MOX fuelled reactor is recycled, then a single wholly MOX fuelled reference reactor on full power could be supported by about 3.5 uranium fuelled PWRs (Figure 10). Alternatively almost all PWRs could be supported in due course with 30 per cent MOX loading. On successive recycles the product plutonium worth would decrease. The injection of fresh plutonium from the uranium-fuelled PWRs would reduce the impact of this (Annex D) although it cannot, of course, increase the value of the multiply recycled plutonium itself.

Table 11 illustrates how MOX fuelled PWRs and BWRs operating in self generating mode change their fuel composition with successive fuel reloads.

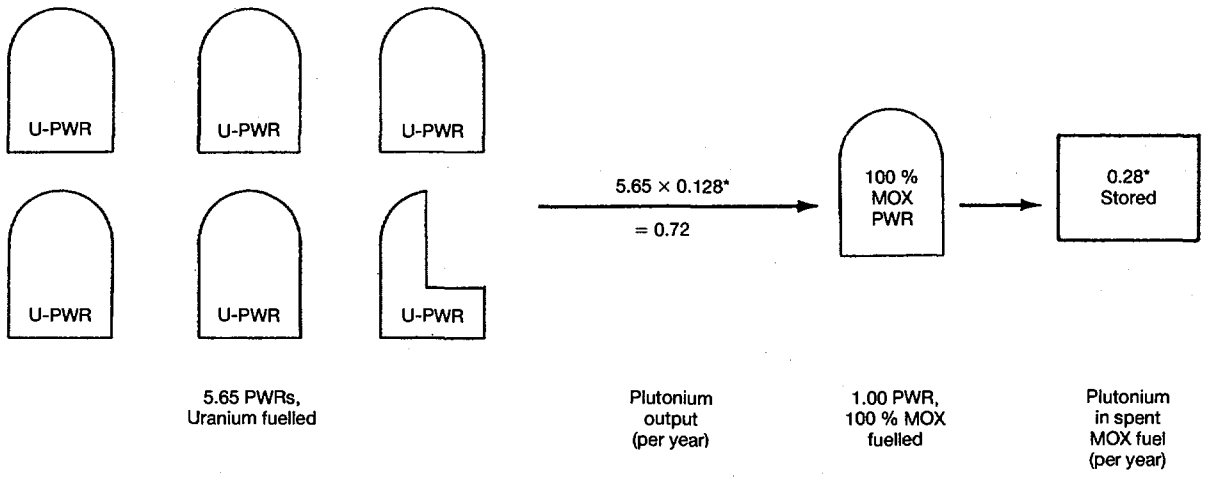
2.4.6 Plutonium in Fast Reactors

The attraction of the fast reactor has been its potential to breed more fuel than it consumes. The factor B (Section 1.6.1):

$$B = \Psi - 1 - L$$

can be designed to be greater than unity so that there is a net gain of fissile material. The breeder reactor is not only self sufficient in fuel but it can also yield the fuel needed to start further reactors.

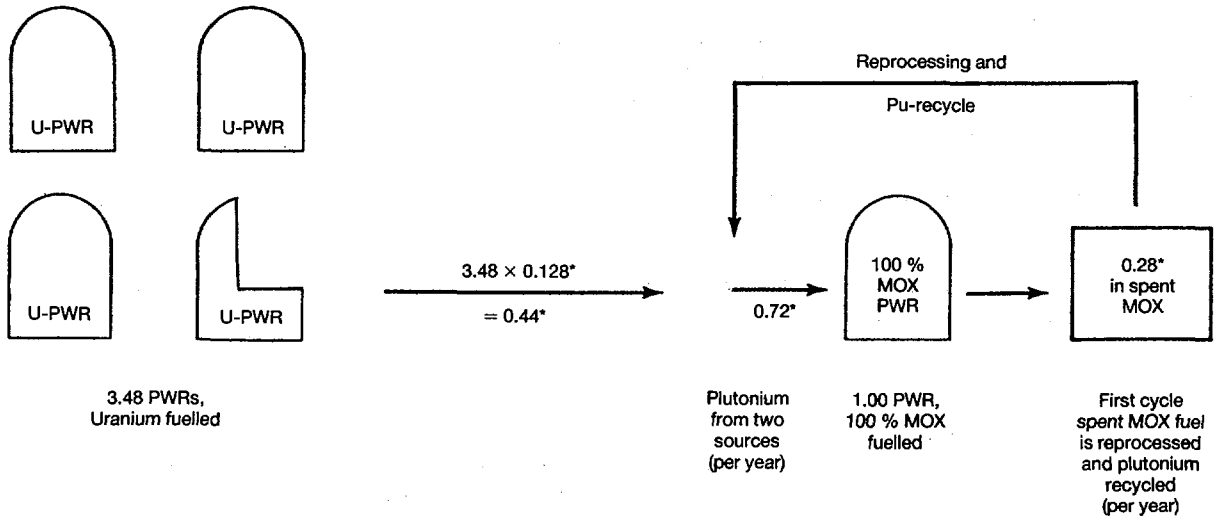
Figure 9. **ONCE THROUGH MOX FUEL**[1]



* Units: Tonnes Pu_{eq} thermal (after 4 years spent fuel storage and 2 years fuel fabrication).

1. All reactors are 1000 MWe reactors. Original calculations are based on the 900 MWe reference reactor as used for the nucleonics calculations in this report. No allowance was made for down times.

Figure 10. **PLUTONIUM PRODUCTION AND RECYCLE, MOX FUEL REPROCESSED**[1]



* Units: Tonnes Pu_{eq} thermal (after 4 years spent fuel storage and 2 years fuel fabrication).

1. All reactors are 1000 MWe reactors. (See also footnote Fig. 9).

In the early days of fast reactor development a great deal of attention focussed on getting high breeding gains in order to facilitate rapid introduction of fast reactors into the electricity system, starting with a relatively small stock of separated plutonium. Although high gains can be achieved, more attention has been devoted in recent years to reducing fast reactor costs even if this sacrificed some breeding gain.

The ability for fast reactors to breed is a matter of design and choice, not one of necessity and they can be used in a self-sustaining mode (no net production or loss) or as plutonium burners with a net consumption. Even when operating as breeders their net plutonium yield per GWey of electricity output will be less than that from a PWR operating with once-through fuel, a fact that is still not widely recognised (Table 10).

The total fissile material consumption of a fast reactor per GWey is broadly the same as a thermal reactor's although significant thermal efficiency differences arise from operational temperature differences (c.a. 20 per cent). Both consume 1 tonne of fissile material per GWey in round terms but whereas the PWR operating in the once-through mode needs 150 tonnes of natural uranium to supply this the fast reactor needs only 1 tonne of depleted uranium, thus saving some 150 tonnes of uranium per GWey.

The energy worth of plutonium from LWR fuel is higher in a fast reactor than a thermal reactor. Plutonium-238, plutonium-240 and plutonium-242 are fissile in fast neutron fluxes (Table 5) and this means that the fast reactor is able to use plutonium that has been recycled in PWRs far more efficiently than PWRs themselves.

Figure 11 illustrates the effect of a MOX burning PWR on fast reactor plutonium availability. 5.65 uranium fuelled 1 GWe PWRs, produce sufficient plutonium (1.43 tonne Pu_t) to fuel one wholly MOX fuelled PWR for a year (gross consumption 0.72 tonne fissile Pu_{eq} thermal) or 1.9 plutonium fuelled fast reactors (gross consumption 1.1 tonne Pu_{eq} fast) for a year. The 1 GWe MOX PWR produces 1.04 tonne Pu_t which is sufficient to provide the gross annual consumption of 1.2 fast reactors.

The plutonium from spent MOX thermal reactor fuel could be recycled in PWRs or saved for fast reactors where its energy worth would be significantly higher. However the fissile worth of stored plutonium decreases with time, as has been described earlier and is shown in Figure 7. The decline depends on the initial isotopic composition and will also be dependent on the type of reactor (thermal or fast) in which the mixed oxide fuels are to be used.

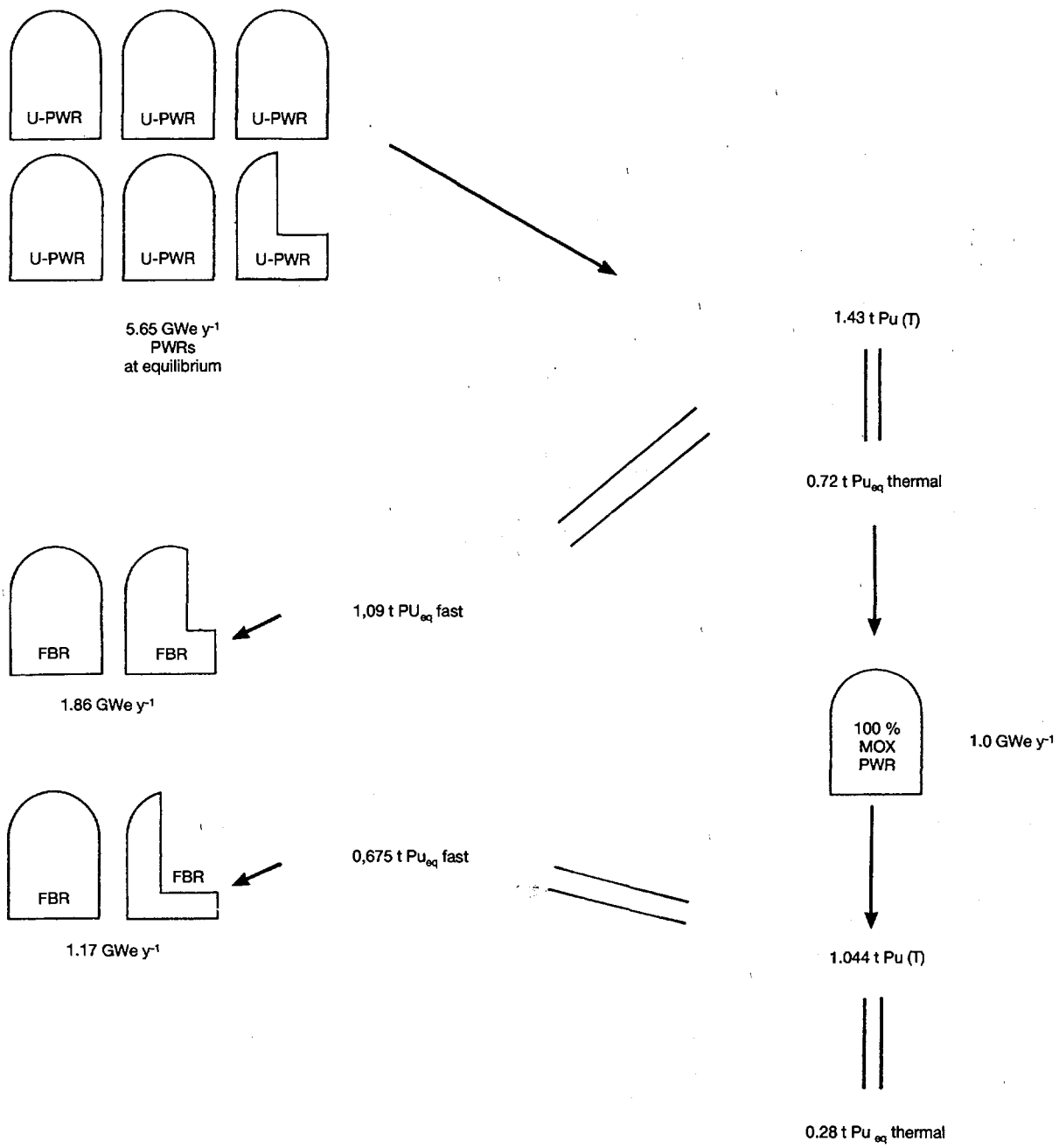
The use of plutonium in PWRs would reduce the rate at which fast reactors could be deployed if plutonium stocks were feared to be insufficient to meet their initial inventories, but the situation might be alleviated if nitride or carbide breeder reactor fuels were available and proven for use in preference to the oxides.

2.4.7 Plutonium in Thorium-Burning Thermal Reactors

One possible use for plutonium is to recycle it with thorium as the fissile material in thermal reactors (ref. 32). When an atom of thorium-232 absorbs a neutron it eventually becomes uranium-233, which is an excellent thermal-reactor fuel. This cycle is attractive in the very long term because the world's resources of thorium are about three times those of uranium, so that the energy potential of thorium is greater by about the same factor (32).

Present evidence indicates that the thorium cycle can be run as a conversion cycle ($B < 0$) or as a self-sustaining cycle ($B = 0$). But increasing B entails rapidly increasing cost for low burnup and/or low specific power and/or frequent fuel unloading. A breeding cycle using thorium is at best marginal and the long-term choice is likely to be a high conversion reactor, a self-sustaining cycle, or uranium-233 production in a fast reactor for subsequent use in thermal reactors (burner/breeder symbiotic cycle).

Figure 11. **COMPARATIVE ANNUAL PLUTONIUM FUEL REQUIREMENTS FOR 100 % MOX FUELLED PWR AND FOR FBR[1]**



1. All reactors are 1000 MWe reactors (see also footnote Fig. 9).

These sorts of cycles require an initial fissile inventory approximately proportional to the total installed capacity. Plutonium is a useful option as the initial fissile material and enriched uranium could also be used. Thus, the total installed capacity (as distinct from the energy available from thorium) would be restricted by shortage of these materials.

Consequently, the consumption of plutonium and uranium-235 in conversion reactors could reduce the ultimate ability to use thorium unless the burner/breeder cycle is used.

2.4.8 The Present Situation

The preceeding Sections 2.4.1 to 2.4.6 have looked at reactors operating in isolation. In practice many utilities in OECD countries have been operating reactors for a long time and the majority of OECD countries with nuclear power reactors have been having some of their spent fuel reprocessed.

The present situation is therefore one in which stockpiles of plutonium of varying origins and ages exist and material is available to feed into MOX manufacture and use in existing reactor types. Several OECD countries are already burning MOX in PWRs and/or fast reactors. The available plutonium has come from earlier generations of fuel including lower burn-up gas/graphite fuels and its isotopic composition will not in general be the same as that now being produced in LWR spent fuel.

Much of the spent fuel currently being removed from LWRs in countries which plan to reprocess it will still be stored for up to ten years before being reprocessed due to the accumulated backlog of spent fuel that has built up.

The detailed logistic calculations undertaken for this study have centred on plutonium freshly recovered from spent fuel from PWRs after 4 and 10 year cooling periods. Attention has also been concentrated on the first recycle since fuel undergoing a second recycle is not likely to be used before the year 2000 at the earliest. These "reference" cases are not necessarily typical of any one country but they provide a reasonable basis for comparison with other variants, as will be seen later.

2.4.9 Core Physics Calculations

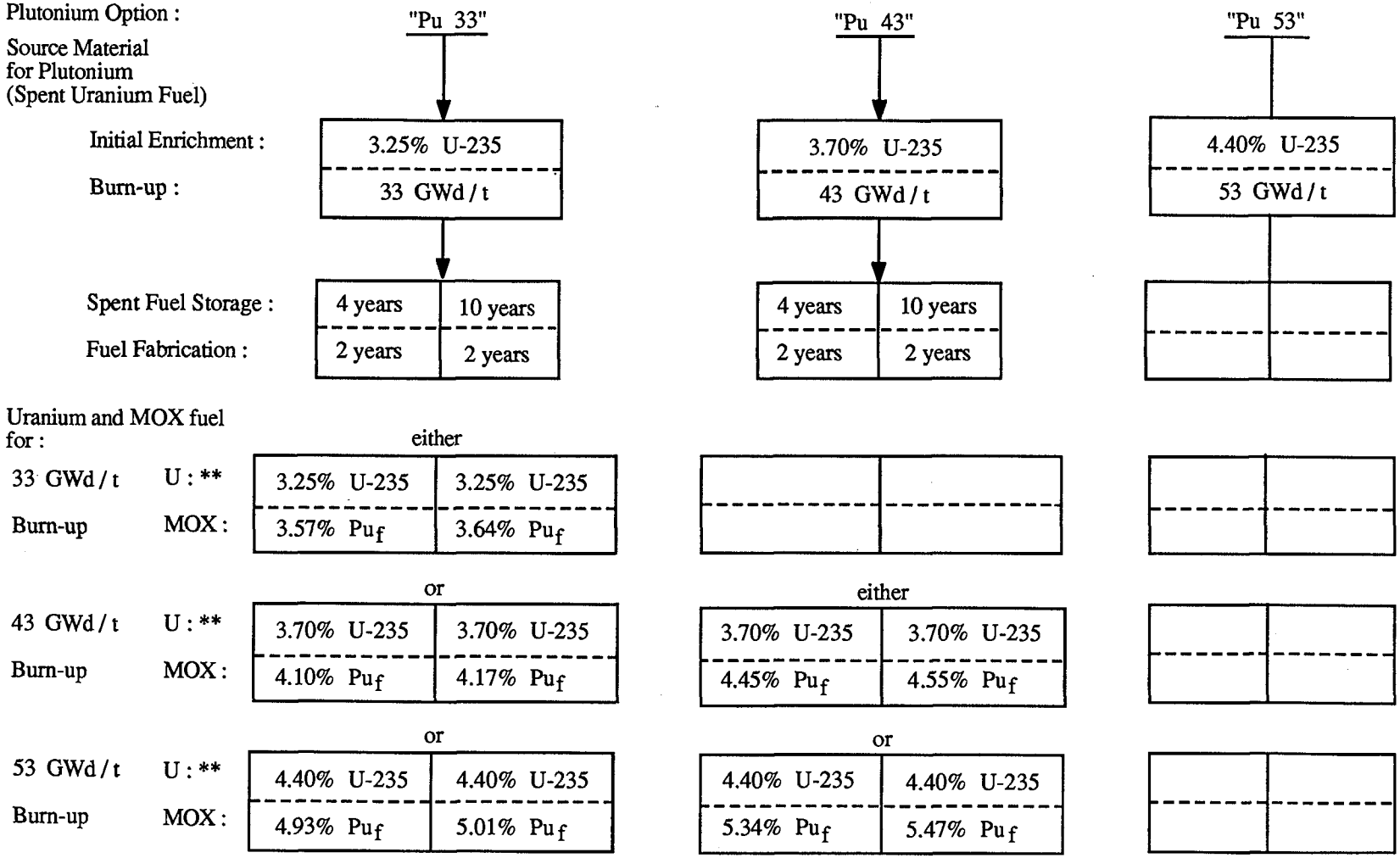
For reasons set out above the specific examples examined in the study relate to MOX fuel use in existing PWRs. Calculations have been performed for fuel batches in a 17 x 17 matrix PWR at equilibrium. The reactor is assumed to have been brought to equilibrium using uranium fuel for which a 30 per cent MOX loading is then substituted.

To illustrate the effect of changing assumptions PWR fuel enriched to 3.25 per cent, 3.7 per cent and 4.4 per cent uranium-235 is used with burn-ups of 33 000, 43 000 and 53 000 GWd per tonne respectively, based on annual replacement of one third, one quarter or one fifth of the core fuel respectively, with in-core residence times of 3, 4 and 5 years. MOX fuel is produced using plutonium recovered after 4 and 10 years storage of this spent uranium fuel, followed by 2 years in the subsequent fabrication stages. It is also designed for burn-ups of 33 000, 43 000 and 53 000 MWd per tonne. The MOX fuel is assumed to be produced using depleted uranium with a uranium-235 content of 0.225 per cent.

It was considered on the basis of previous studies (22) that there would be no complicating problems arising from the use of MOX fuel at 30 per cent of the total fuel in the PWR core.

The thirteen fuel cases considered and their relationships to one another are illustrated in Figure 12 and the isotopic compositions before and after irradiation are presented for uranium fuels in Table 9 and for plutonium fuels in Table 12.

Figure 12. **FUEL RELATIONSHIPS IN THE CALCULATED CASES***



* The numbers 33, 43 and 53 characterize the burn-up in GWd / t of the spent fuel from which plutonium will be recovered.

** From enrichment of natural uranium.

Table 12 A

PWR MOX FUEL

ISOTOPIC BALANCE FOR ONE TONNE OF FUEL
FABRICATED WITH PLUTONIUM FROM 33 000 MWD/TONNE URANIUM OXIDE SPENT FUEL ("Pu 33")

(as weight per tonne in [kg] and as percentage [%] of total U for uranium and of total Pu + Am for plutonium and for americium)

FUEL SPECIFICATION / ISOTOPE: / UNIT:	U-235 kg	U-235 %	U-236 kg	U-236 %	U-238 kg	U-238 %	U-tot kg	Pu-238 kg	Pu-238 %	Pu-239 kg	Pu-239 %	Pu-240 kg	Pu-240 %	Pu-241 kg	Pu-241 %	Pu-242 kg	Pu-242 %	Am-241 kg	Am-241 %	Pu-tot* kg	Pu/Pu + U** %
"Pu 33"																					
4 years spent fuel storage																					
3.57 % Pu_f+	2.13	0.22	0.0	0.0	946.32	99.78	948.45	0.7	1.35	30.19	58.56	12.15	23.57	5.5	10.67	2.48	4.81	0.54	1.04	51.55	5.15
33 000 MWd/t++	1.13	0.12	0.21	0.02	924.97	99.86	926.31	0.84	2.15	15.62	39.86	12.30	31.39	6.7	17.11	3.2	8.16	0.52	1.33	39.18	4.06
4.10 % Pu_f+	2.12	0.22	0.0	0.0	938.71	99.78	940.83	0.8	1.35	34.65	58.56	13.94	23.57	6.31	10.67	2.85	4.81	0.62	1.04	59.17	5.92
43 000 MWd/t++	0.97	0.11	0.23	0.03	911.25	99.87	912.46	1.06	2.50	15.91	37.67	13.51	32.00	7.45	17.63	3.69	8.74	0.62	1.46	42.23	4.42
4.93 % Pu_f+	2.09	0.22	0.0	0.0	926.67	99.78	928.76	0.96	1.35	41.72	58.56	16.79	23.57	7.6	10.67	3.43	4.81	0.74	1.04	71.24	7.12
53 000 MWd/t++	0.89	0.10	0.25	0.03	894.08	99.87	895.22	1.38	2.83	17.83	36.66	15.76	32.40	8.64	17.76	4.24	8.71	0.80	1.64	48.65	5.15
10 years spent fuel storage																					
3.64 % Pu_f+	2.13	0.22	0.0	0.0	944.8	99.78	946.93	0.7	1.32	32.01	60.32	12.88	24.27	4.47	8.33	2.63	4.95	0.43	0.81	53.07	5.31
33 000 MWd/t++	1.14	0.12	0.21	0.02	923.52	99.85	924.86	0.79	1.95	16.42	40.38	13.06	32.12	6.76	16.62	3.15	7.74	0.49	1.19	40.66	4.21
4.17 % Pu_f+	2.11	0.22	0.0	0.0	937.13	99.77	939.25	0.8	1.32	36.65	60.32	14.75	24.27	5.06	8.33	3.01	4.94	0.49	0.81	60.75	6.08
43 000 MWd/t++	0.98	0.11	0.23	0.03	909.74	99.87	910.96	0.99	2.26	16.67	38.09	14.32	32.72	7.57	17.30	3.63	8.28	0.59	1.34	43.77	4.58
5.01 % Pu_f+	2.09	0.22	0.0	0.0	924.98	99.78	927.07	0.96	1.32	43.99	60.32	17.70	24.27	6.08	8.33	3.61	4.95	0.59	0.81	72.93	7.29
53 000 MWd/t++	0.90	0.10	0.25	0.03	892.47	99.87	893.62	1.28	2.55	18.64	37.05	16.67	33.13	8.79	17.48	4.16	8.27	0.77	1.53	50.31	5.33

Table 12 B

PWR MOX FUEL

ISOTOPIC BALANCE FOR ONE TONNE OF FUEL
FABRICATED WITH PLUTONIUM FROM 43 000 MWD/TONNE URANIUM OXIDE SPENT FUEL ("Pu 43")

(as weight per tonne in [kg] and as percentage [%] of total U for uranium and of total Pu + Am for plutonium and for americium)

FUEL SPECIFICATION / ISOTOPE: / UNIT:	U-235 kg	U-235 %	U-236 kg	U-236 %	U-238 kg	U-238 %	U-tot kg	Pu-238 kg	Pu-238 %	Pu-239 kg	Pu-239 %	Pu-240 kg	Pu-240 %	Pu-241 kg	Pu-241 %	Pu-242 kg	Pu-242 %	Am-241 kg	Am-241 %	Pu-tot* kg	Pu/Pu + U** %
"Pu 43"																					
4 years spent fuel storage																					
4.45 % Pu_f+	2.10	0.22	0.0	0.0	930.53	99.77	932.63	1.29	1.91	36.78	54.60	16.59	24.62	7.68	11.40	4.28	6.36	0.75	1.11	67.37	6.74
43 000 MWd/t++	1.02	0.11	0.23	0.03	903.61	99.86	904.86	1.47	3.01	18.06	36.95	15.54	31.80	8.43	17.26	4.60	9.40	0.77	1.57	48.88	5.13
5.34 % Pu_f+	2.07	0.22	0.0	0.0	916.31	99.78	918.38	1.56	1.91	44.57	54.60	20.10	24.62	9.31	11.40	5.19	6.36	0.91	1.11	81.62	8.16
53 000 MWd/t++	0.94	0.11	0.24	0.03	884.43	99.87	885.62	1.89	3.33	20.57	36.13	18.37	32.25	9.83	17.26	5.28	9.27	1.01	1.77	56.95	6.04
10 years spent fuel storage																					
4.55 % Pu_f+	2.09	0.22	0.0	0.0	928.20	99.78	930.29	1.32	1.89	39.29	56.35	17.71	25.41	6.22	8.92	4.58	6.57	0.60	0.86	69.71	6.97
43 000 MWd/t++	1.03	0.11	0.23	0.02	901.35	99.86	902.61	1.41	2.76	19.15	37.46	16.68	32.61	8.58	16.78	4.58	8.96	0.73	1.43	51.13	5.36
5.47 % Pu_f+	2.06	0.22	0.0	0.0	913.47	99.78	915.53	1.60	1.89	47.60	56.35	21.46	25.41	7.53	8.92	5.55	6.57	0.73	0.86	84.47	8.45
53 000 MWd/t++	0.95	0.11	0.24	0.03	881.71	99.87	882.90	1.81	3.03	21.86	36.65	19.73	33.08	10.03	16.82	5.26	8.81	0.97	1.62	56.66	6.33

* Pu total + Am.
** Pu total + Am/Pu total + Am + U total.
\+ Before irradiation.
++ After irradiation.

2.5 Economics of Plutonium Recycle

2.5.1 General

The economics of plutonium use in thermal reactors depends in part on the economics of the uranium fuel cycle and in part on costs peculiar to plutonium and mixed oxide fuel. In the former the price of uranium and separative work are the important *front-end* items (4) whereas in the latter fuel fabrication costs are dominant, with MOX fuel fabrication replacing all* or part* of the mining and concentration stages and all of the conversion, enrichment and fabrication stages of uranium fuel manufacture. The stages of the two fuel cycles are set out in Figure 13.

The back-end of the two fuel cycles (i.e. the stage after removal of spent fuel from the reactor) is essentially the same with the same options of short or long term spent fuel storage followed by reprocessing or alternatively of spent fuel disposal.

Decisions on whether or not to use plutonium will also be influenced however by the extent to which its recovery costs have been or remain to be met, as described in the next section.

2.5.2 Economic Methodology

In previous studies of the economics of nuclear power (27, 28) and the nuclear fuel cycle (4), NEA expert groups have adopted a levelised lifetime costs approach in constant money terms in which costs per unit of electricity output are "averaged" over the whole life of a reactor. The method and the reasons for its adoption have been described in detail in the reports of these groups. (See Annex E for a brief description of the method).

The method has limitations in that it does not take interactions between existing and future generating plants on an interconnected network (or grid) into account. This has not mattered for the purposes of the earlier studies although they noted that new plant investment decisions may be better based on an examination of the projected costs of operating the whole electricity generation system, both with and without the different types of new plant under consideration. Suitably planned systems cost studies are able to simulate the effects of merit order operation and bring out the impacts they would have on the load factors (and hence unit costs) of different plant types.

In the case of nuclear fuel cycle costs the load factor of the reactor is not very important (4), although it can affect the relative contribution of the costs of the initial core fuel and those of subsequent reloads in the levelised overall reactor lifetime fuel costs.

The costs of plutonium fuel use are also *better* looked at in terms of overall system costs since this avoids the problem of arbitrarily allocating the costs of spent uranium fuel reprocessing (i.e. plutonium recovery) to either the uranium fuel cycle or the MOX cycle. For uranium fuel used in once-through mode the relevant costs are as shown to the left of line AOE in Figure 14. For reprocessing cycles the costs can be divided between the uranium feed fuel and recovered plutonium for use in MOX, to the left and right of lines AOD, AOF or even AOC (Figure 14), depending on how the reprocessing and storage costs are allocated.

The use of system costs also facilitate the examination of the effects of multiple recycle of plutonium and uranium and of the deferment of plutonium use until economic fast reactors are available.

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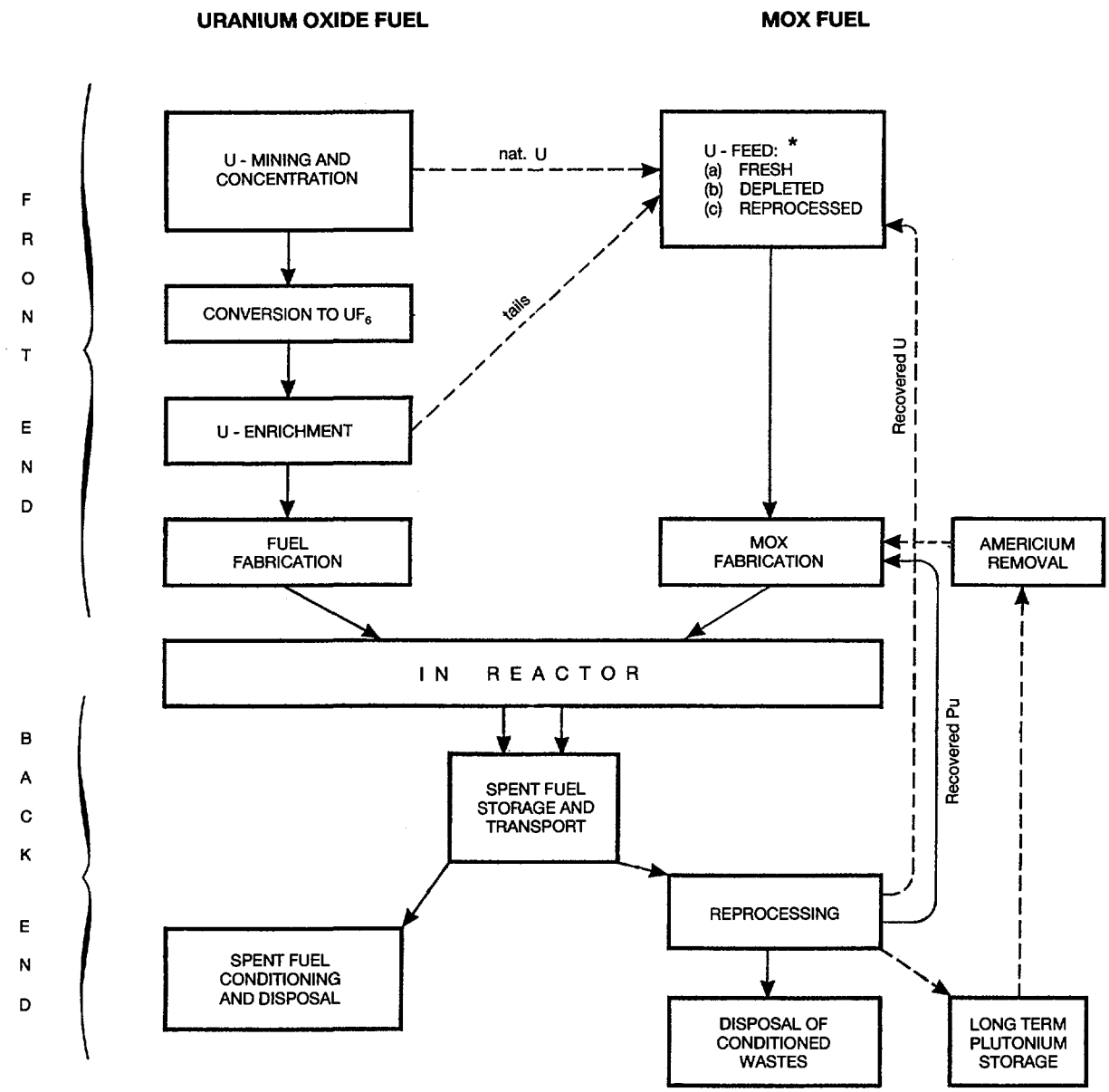
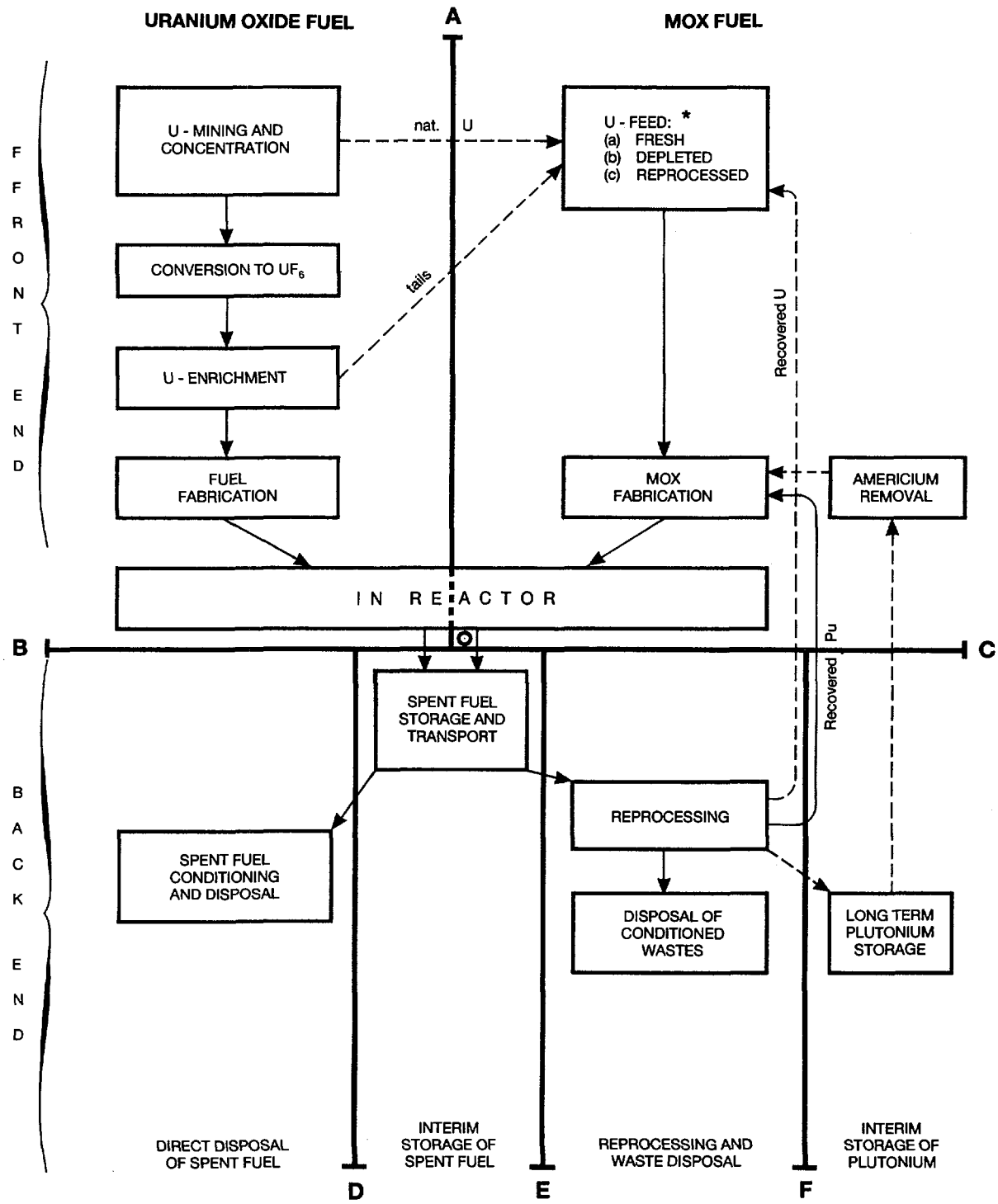
* Depending on whether natural uranium or depleted or reprocessed uranium is used in the MOX fuel.

Figure 13. **THE STAGES FOR THE URANIUM OXIDE AND MIXED OXIDE FUEL CYCLES FOR THE PWR**



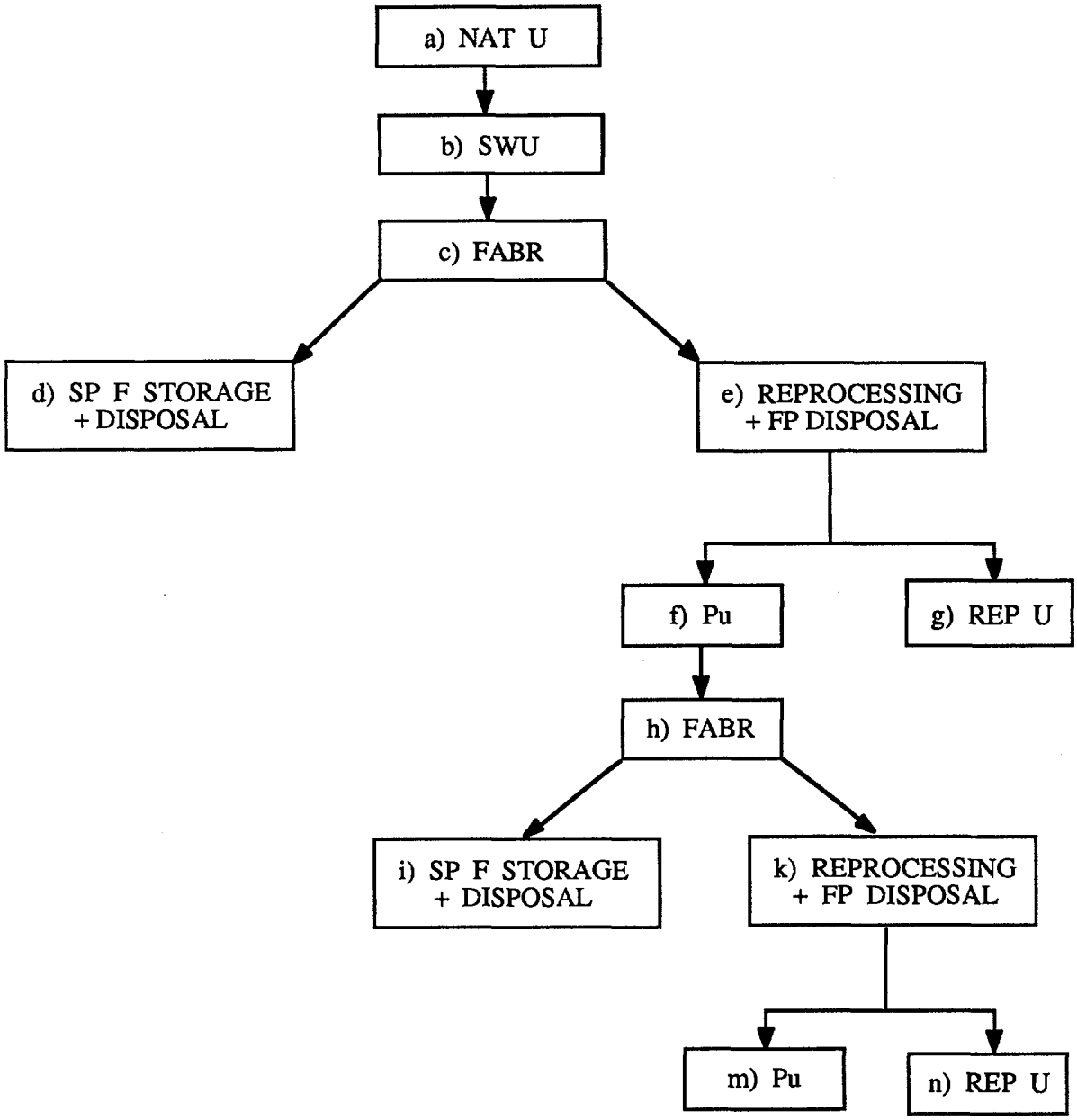
* All calculations are based on the use of depleted uranium in MOX fuel.

Figure 14. **POSSIBLE COST ALLOCATIONS FOR THE URANIUM OXIDE AND MIXED OXIDE FUEL CYCLES FOR THE PWR**



* All calculations are based on the use of depleted uranium in MOX fuel.

Figure 15. **SIMPLIFIED STAGE COSTS FOR UO_2 AND MOX FUELS**



Note : *a* to *n* are unit stage costs in $ / kg hm (or SWU) for the stages shown.
For simplicity uranium price *(a)* is taken to include conversion costs.
SP F = spent fuel ; FP = fission products.

Unfortunately system cost studies are specific to the generation system examined, to its existing and (assumed) future plant types, and to the current level and projected growth in electricity demand. For this reason the earlier study of nuclear fuel cycle costs did not look at plutonium fuel cycles in any detail (4).

The decision that this study should focus on plutonium use in PWRs in the *medium-term* greatly simplifies matters too because the plutonium available for use will be that arising from existing or planned reactors which either has been or will be recovered regardless of whether it is to be used in MOX fuel or not. The economics of its use are therefore based on the split at AOC (Figure 14) with costs above and to the right of the line attributable to MOX fuel which can be looked at on a "single reactor" basis in competition with the front end of the uranium cycle; i.e. the full costs of re-processing and waste management are charged to the reactor (uranium or MOX fuelled) producing the wastes. In the simplified format at Figure 15, (a+b+c) can be compared with h. Alternative patterns of cost allocation may be more appropriate for countries where there has been no commitment to reprocess fuels or where the plutonium is recovered specifically for re-cycle. These will also be examined later.

2.5.3 Basic Assumptions

The 1986 study looked at the levelised costs of fuel for a PWR commissioned in 1995 with a 25 year life. It considered the likely long term movement of prices for the various stages of the fuel cycle and the sensitivity of overall costs to variations in the individual stage costs. The costs were all expressed in constant 1st January 1984 US $ and a reference discount rate of 5 per cent was used in constant money terms with 10 per cent as a variant.

For this study the currency unit selected as reference is the 1st January 1987 US $. This introduces some apparent divergences in costs compared with the previous study (4) due to exchange rate variations (see 2.5.4.14) so that basic stage costs are also presented in European Currency Units (ECU) of 1st January 1987. A table of exchange rates for January 1987 and January 1984 is provided (Table 13) to facilitate comparisons and show the extent of currency movements. The same reference and variant discount rates are retained.

Attention is concentrated on PWRs in operation in the 1990s rather than a reactor with a specific commissioning date. The implications of longer term changes in the costs of the different fuel cycle stages can then be explored on a comparative basis.

2.5.4 The Costs of the Stages of the Nuclear Fuel Cycle

2.5.4.1 General

The unit costs have been derived by the working group from consideration of published information and responses of participants to a questionnaire prepared for this study. The individual stage costs, which are discussed below, are set out in Table 14.

2.5.4.2 Uranium Prices

In the previous study on nuclear fuel economics the question of future uranium price movements was considered at some length (4). It was argued that the low prices being paid in spot markets were not sustainable indefinitely and that longer term contract prices (with which spot prices should ultimately converge) were a better guide to the levels needed to maintain a healthy and stable uranium supply industry. The surplus uranium stocks that had accumulated during the 1970s were expected to be consumed by the mid-1990s when, provided timely development of new mines was undertaken (5), uranium supply and demand could be back in balance.

Table 13

EXCHANGE RATES

Country	Currency	per US $ at 1.1.84	per US $ at 1.1.87
Australia	Dollar	1.120	1.504
Austria	Schilling	19.341	13.710
Belgium	Franc	55.640	40.410
Canada	Dollar	1.244	1.380
Denmark	Krone	9.875	7.342
Finland	Markka	5.810	4.794
France	Franc	8.347	6.455
Germany	DM	2.724	1.941
Greece	Drachma	98.670	138.760
Ireland	Pound	0.881	0.714
Italy	Lira	1659.500	1358.130
Japan	Yen	232.200	159.010
Netherlands	Gulden	3.064	2.192
New Zealand	Dollar	1.528	1.910
Norway	Krone	7.742	7.400
Portugal	Escudo	131.650	146.117
Spain	Peseta	156.700	132.395
Sweden	Krona	8.001	6.819
Switzerland	Franc	2.179	1.623
Turkey	Pound	282.800	757.790
United Kingdom	Pound	0.689	0.678
EC	ECU	1.211	.927

Market developments since the publication of the earlier study have made the highest of the price projections look less likely now, although cyclical fluctuations could occur, as in other commodity markets, and perturbations could still arise directly from political acts affecting uranium itself or indirectly through effects on other fuels. In this study uranium price is treated as an independent variable for illustrative calculation purposes and results are presented as functions of natural uranium price.

The prices used for illustration range from $20 to $40 per lb U_3O_8 ($50 to $100 per kg U) which span current contract prices and could persist into the 1990s. Higher and lower values are possible but the relationship of fuel cost to uranium price is linear so that readers can extrapolate to match their own judgements.

2.5.4.3 Uranium Conversion

The costs of conversion of natural uranium oxide to uranium hexafluoride for enrichment have not changed significantly since the previous study. A price of $7 per kg U has been adopted for the reference case. The sensitivity of overall costs to this parameter was shown to be low in the earlier work (4) so a single value is adopted here.

The costs of conversion of recycled uranium from oxide to hexafluoride for re-enrichment have been quoted (26) as $18 per kg. This stage is not necessary in MOX fabrication and any costs of conversion to oxide are included either in the reprocessing or the fabrication costs.

Table 14

UNIT COSTS USED IN COST CALCULATION*
for the period of the mid to late 1990s

Component	Illustrative cost range**	Illustrative values adopted for computations	Comment
Uranium	$50 ~ $100/kg U (ECU 48 ~ ECU 96/kg U)	$80/kg U (ECU 75/kg U)	
Conversion to UF_6	—	$7/kg U (ECU 6.5/kg U)	
Enrichment	$70 ~ $130/SWU (ECU 65 ~ ECU 120/SWU)	$100/SWU (ECU 90/SWU)	Current price $110/SWU (ECU 100/SWU)
UO_2 Fuel Fabrication	$175 ~ $300/kg U ECU 160 ~ ECU 280/kg U	$200/kg U ECU 185/kg U	National costs could differ from illustrative cost range.
MOX Fabrication	ECU 650 ~ ECU 925/kg HM ($700 ~ $1000/kg HM)	ECU 740/kg HM ($800/kg HM)	
Reprocessing	ECU 460 ~ ECU 920/kg HM ($500 ~ $1000/kg HM)	ECU 790/kg HM ($850/kg HM)	Includes allowance for waste storage. Excludes HLW disposal.
Reprocessed U value		73 % to 82 % of U with same enrichment level	
Pu Storage	ECU 0.9 ~ ECU 1.8/g Pu tot/yr ($1 ~ $2/g Pu tot/yr)	—	For short periods included in reprocessing costs.
Pu Purification	ECU 9 ~ ECU 26/g Pu tot ($10 ~ $28/g Pu tot)	ECU 17/g Pu tot ($18/g Pu tot)	

* In 1st January 1987 dollars.

** The shown cost range includes controversial positions.

Note: The costs of spent fuel storage, conditioning and disposal and reprocessing waste conditioning and disposal were not re-assessed for this study.

2.5.4.4 Enrichment

The previous study (4) described the then current position on enrichment technology and the market price being charged for separative work. After consideration of the likely pace of technological and market development a conservative figure of $130 per SWU was adopted with a range of $100 to $150 and a sensitivity variant of $70 per SWU, to allow for major technological advance.

Even before the report had appeared a highly competitive market with considerable excess enrichment capacity (5) had brought prices down to $100 per SWU or less but the decline in the value of the US $ has reversed this trend. For the present study it is considered that a price of $100 per SWU is an appropriate reference case for the 1990s. There is a possibility that prices may remain higher at up to $130 per SWU or that they may fall to or even below $70 per SWU in the long term as existing plant investment is written off and advanced centrifuge and laser technologies are deployed. It would be unwise at this stage to assume that very low prices could prevail in the 1990s and early 2000s, not least due to the long lead time for penetration of the newer technologies.

The uranium-235 content of enrichment plant tails would be reduced for maximum economy with declining separative work costs and/or rising uranium prices. The relative price movement determines the optimum tails composition. The level assumed in this study is 0.225 per cent which has not been optimised in relation to separative work and uranium price assumptions.

The costs of re-enriching the uranium recovered from spent PWR fuel, which, at low burn-ups, may contain more uranium-235 than natural uranium, is likely to be somewhat higher than the above values due to its higher radioactivity. Additionally extra separative work is required to produce the enrichment needed to offset the neutron absorption of uranium-236 which concentrates in the recycled uranium.

For uranium from LWR fuel the extra separative work needed is about 10-20 per cent but this is roughly equivalent to the separative work "stored" in the recovered uranium so that the separative work per kg of fuel is about the same for natural and recycled uranium. The basic cost of separative work may however be somewhat higher (25) and based on this and group discussions an allowance of plus 10 per cent in a range 0 per cent to 20 per cent is included for separative work prices (per SWU) where appropriate.

2.5.4.5 Uranium Oxide Fabrication Costs

Fabrication costs for uranium dioxide fuels differ from country to country due partly to the fact that several countries have opted to enter this market and have plants of different sizes and ages, and partly to the movement of currencies which has had a dramatic effect on the apparent relativity between US costs and those in other countries in recent years.

For conventional PWR fuel produced from fresh uranium and designed for 33 000 MWd per tonne burn-up the fabrication cost for illustrative calculations has been taken as $200 per kg U but this is not typical of Europe or Japan whose costs lie above this at current exchange rates. The full range across OECD currently is from $200 per kg to $300 per kg but for the future prices could fall to between $175 and $250. Sensitivity analyses are included in this study at $175 per kg and $300 per kg. Fuels designed for extended burn-up could have slightly higher fabrication costs per kg of heavy metal due to the possible incorporation of burnable neutron absorbers and other minor changes e.g. adjust the rod length to allow for larger dimensional changes. They are mostly start-up and overhead costs which would not affect longer term mass produced fuels in a competitive market (29). The main factor influencing the price per kg HM of fresh high burn-up fuel is the extra separative work and natural uranium required to get the higher initial enrichments. (These higher costs are more than offset by higher electricity output so the costs per unit of electricity output are less).

Recycled uranium recovered from spent fuel contains uranium-232 which decays to yield the high energy gamma-emitter thallium-208, the concentration of which builds up to an equilibrium value after about 10 years storage. It also contains higher concentrations of gamma-emitting natural uranium-234 and the strong neutron absorber uranium-236 as well as traces of transuranic elements and fission products.

The fabrication of fresh fuel with uranium recovered from spent fuel therefore requires use of some screening to protect the workforce. This requirement may decrease or disappear if the product is processed in dilution with natural uranium, or if the transit time in each fabrication stage is rapid enough. A premium over natural uranium dioxide of about $30 per kg for fabrication is appropriate. If the reprocessed uranium is used for MOX fabrication some premium should be taken into account to allow for the conversion of reprocessed uranium into sinterable uranium oxide.

2.5.4.6 Mixed Oxide Fuel Fabrication

Because of its radiotoxicity (see Section 1.5) plutonium oxide is kept in sealed vessels or handled in glove boxes at sub-atmospheric pressures. In the event of leakage, air is pulled inwards away from operators and the gases discharged to the atmosphere pass through filters to remove any traces of plutonium.

Working areas that are likely to become contaminated due to the need to dismantle or otherwise move equipment are isolated and access is gained through air locks in full protective clothing with an external air source. Working areas which are not likely to be contaminated require only conventional protective equipment to avoid the spread of accidental contamination. Access is controlled and air quality monitored so that an evacuation can be effected and remedial steps taken if any release of plutonium should occur.

As had been indicated in Section 1.4 the fabrication of MOX fuel for PWRs is complicated by the presence of americium-241, by the decay products of plutonium-236 (and uranium-232), by the heat output from plutonium-238 and by the neutron activity (from spontaneous fission and alpha-n reactions).

The MOX fabrication plant layouts and physical controls are designed to ensure that present radiation protection standards are met for both workers and the general public.

These precautions and stringent plutonium accountancy for safeguards and safety reasons inevitably make plutonium handling much more expensive than that of natural uranium, but a lot of technical experience now exists for both thermal and fast reactor fuel fabrication (see for example refs. 25, 30, 31).

Fabrication is affected by the need to produce intimately intermixed oxides of plutonium and uranium which have a carefully controlled composition that varies depending on the intended use of the fuel (31). If further recycling is intended the solubility of the spent fuel is an important consideration in its fabrication.

In current plants MOX fuel fabrication costs are higher than those of ordinary uranium oxide fuels, i.e. $700-$1300 per kg HM. In the mid 1990s costs may be around $1000 per kg but as MOX fuel is used on a significant scale they will decline and by the late 1990s costs could lie in the range $750-880 per kg HM with the possibility of further decreases in the long term (Table 14). These prices include engineering services and transport of the fuel to the reactor. These MOX fabrication costs are based on experience and uranium fuel fabrication costs in Europe rather than the US, although differences in uranium oxide fabrication costs themselves do not have a great impact on overall fuel costs (see Table 15).

Table 15

EFFECT OF FABRICATION COST ON COSTS PER KWH FOR REPLACEMENT FUELS USING FREE PLUTONIUM

Burn-up (MWd/t)	Fuel cost* (mills/kWh)					
	UO_2 fuel*			MOX fuel**		
	UO_2 Fabricat. = $175/kg	UO_2 Fabricat. = $200/kg	UO_2 Fabricat. = $300/kg	MOX Fabricat. = $700/kg	MOX Fabricat. = $800/kg	MOX Fabricat. = $1000/kg
33 000	5.14	5.25	5.67	2.98	3.41	4.26
43 000	4.65	4.73	5.06	2.34	2.68	3.35
53 000	4.66	4.72	5.00	1.94	2.22	2.78

* Natural uranium as used for uranium fuel = $30 per lb U_3O_8
Conversion (U_3O_8 - UF_6) = $7 per kg
Enrichment = $100 per SWU

** Tail uranium, used for MOX = $0 per kg

2.5.4.7 Interim Spent Fuel Storage

The nuclear fuel economics study (4) showed considerable variations in the estimates of the costs of spent fuel storage. These arose from differences of scale, different storage concepts, different periods of storage and economic and financial differences between countries which are reflected in factor costs but which are not necessarily fully reflected in exchange rates. This latter effect can lead to major distortions in capital cost comparisons between countries and apparent changes in relative costs over time (27).

Little has emerged in the intervening period to clarify or simplify the position. The figures adopted in the earlier study for away-from-reactor wet storage of PWR fuel assemblies are equivalent in 1987 US $ to a fixed $50 per kg heavy metal plus $5T per kg within a range of plus or minus 50 per cent, where T years is the period of storage. The formulation (50 + 5T) is made up of a virtually fixed loading, supervision and unloading charge ($50) and a variable capital charge ($5T) which is smallest for stores with high unit throughput, i.e. short fuel storage times. The empirical formula gave the approximate discounted (i.e. present worth) cost at the time the fuel is delivered to the store.

Pending the re-evaluation of spent-fuel storage and disposal costs in forthcoming NEA studies no values are recommended in this study for these parameters. However, where fuel is sent for reprocessing the interim storage costs at the reprocessing plant are included in the overall reprocessing cost.

2.5.4.8 Fuel Transportation Costs

The transfer costs for fresh uranium oxide or MOX fuels are included in their respective fabrication costs.

Spent fuel transport costs vary widely depending on distance and the nature of the journey but they too are only a small fraction of overall fuel costs. The costs of spent MOX transport are similar to those for uranium fuels provided they are cooled for a little longer in the reactor pond.

In the fuel cycle economics study (4) they are taken as $40 per kg heavy metal in 1984 money which is equivalent to $45 in 1987 money values within Europe or the USA.

2.5.4.9 Reprocessing Costs

The costs of reprocessing spent oxide fuel were looked at in some detail in the earlier study (4), based on the detailed cost data published by BNFL at the UK Sizewell Inquiry. In order to arrive at a price for reprocessing services assumptions were made by the NEA working party on profit levels, and BNFL's own conservative assumptions were retained for plant life, plant loading and decommissioning costs.

The results were consistent with published French costs, with the contemporary study by FRG on the back-end of the fuel cycle (33) and with what was known about contract prices. For plants of 1200 tonnes p.a. capacity it was concluded that prices of around $750 per kg HM (excluding short term buffer storage of spent fuel) would provide a return on capital of 10 per cent p.a. or $570 per kg at 5 per cent return, both at the time of reprocessing. For smaller scale plant, for higher rates of return, or as a measure of technical uncertainty a higher figure of $1000 per kg HM was considered appropriate. For larger plant perhaps with lower financial returns, and bearing in mind the conservatism in the underlying assumptions (4) a lower figure of $500 per kg HM was regarded as reasonable. A reference value of $750 per kg HM was adopted (+ $250 per kg HM) in 1984 for the price at the time of feeding into the reprocessing plant. This was equivalent to $724 per kg HM at the time of delivery to the reprocessing site with the costs of 2 years short term buffer storage included. These prices included low level waste conditioning, intermediate level waste conditioning and storage and the capital and operating costs of high level waste vitrification and storage up to the time of ultimate disposal. Other waste conditioning and disposal costs were excluded.

The equivalent figure from this study questionnaire is around $840 per kg HM (1987 $), although a lower figure (see next paragraph) could be argued to be more consistent with European expectations. This includes interim spent fuel storage, low level waste conditioning, high level waste vitrification and storage, conversion of plutonium nitrate to oxide and plutonium storage for a period of time.

It should be noted that these values for reprocessing services correspond to a roughly constant real cost for the back-end of the reprocessing cycle in the European currencies which provided the basis for the earlier study's calculation (5).

Both BNFL and COGEMA expect reprocessing service prices to decrease in the future when the capital costs of plants have been recovered. A decrease of some 30 per cent in reprocessing contract prices to around $600 per kg HM can be envisaged in the late 1990s from existing plants. This would not necessarily apply to new plants on greenfield sites however, so widely different reprocessing costs may be incurred in different countries. However, growing experience gives confidence that plant lives will be longer than conservatively assumed in the past, and more realistic assessment may reduce capital charges. To cover these cases a range of $500 per kg to $1000 per kg has been adopted although for small scale new greenfield plants costs could lie above this range.

The costs of conditioning of low and intermediate level wastes and vitrification and interim storage of high level wastes are included on a discounted basis in the above costs. The costs of final disposal of wastes are not included. Like spent fuel conditioning and disposal costs they will be one of the topics covered in forthcoming NEA studies.

The presence of significant quantities of long lived actinides in the spent fuel, and its higher volume relative to vitrified fission product wastes, are expected to lead to higher disposal costs for spent fuel than for reprocessing wastes (33).

In a specially designed plant in which MOX is co-processed with uranium fuel, reprocessing need be no more expensive than for uranium fuels alone. Attention has to be paid to criticality constraints if a plant designed for uranium fuels is used for MOX and limitations on throughput might increase unit costs by up to 40 per cent at the extreme. Technical experience with fast reactor fuel containing much higher plutonium concentrations has been completely satisfactory and no untoward problems are expected, provided the uranium and plutonium oxides are intimately mixed so that they form a soluble U/Pu oxide when processed (sintered) (31).

2.5.4.10 Plutonium and Uranium Credits

No specific value is attached to plutonium in this study. It is regarded as "free" if its recovery costs have already been incurred or if a country is committed to its recovery for policy or contractual reasons. In other cases it is priced at its net recovery cost making due allowance for the value of recovered uranium and any savings/costs made or avoided relative to the back-end of the once-through mode of LWR fuel use.

An equivalence value for plutonium can be derived as described in Section 2.6.5 and Annex H, Section 3, by equating the costs of the uranium and MOX fuel cycles.

The value attached to recovered uranium, where this is relevant, is based on the contemporary price of fresh uranium with due allowance for the higher uranium-235 content of spent LWR fuel. A factor of 73 per cent to 82 per cent should be applied (27 per cent to 18 per cent reduction in value) to allow for the deleterious effects of uranium-236 (see Section 2.5.4.4 and Annex H, Section 2, for details).

2.5.4.11 Plutonium Storage and Americium Removal Costs

Published costs of plutonium storage vary widely owing to differences in the size of stores and the other factors mentioned in Section 2.5.4.7. They are usually taken to be in the region of $1 to $2 per g of total plutonium per year. Both the UK and France include the cost of short term storage as a minor component of the overall reprocessing charge but some countries requiring longer term storage are incurring costs of this order.

The only published costs for americium removal from plutonium vary from $9 to $18 per g Pu_t, in January 1987 US $ (24, 43). The expert group considers the cost may vary between $10 and $28 per g Pu_t and believes a price of $18 per g Pu_t would be appropriate for plants treating about 2 tonnes Pu_t per annum. This figure corresponds to removal from plutonium oxide and would be less if the plutonium could be stored as nitrate.

The need to remove americium from stored plutonium will depend on its source, the period of storage and the design of the MOX fuel fabrication plant.

2.5.4.12 Plutonium Transport Costs

The costs of plutonium transport are far higher per kg than those of spent fuel due to the added criticality and physical security constraints. Indicative figures of around $500 to $900 per kg, which will vary with the mode of transport (air, land or sea), are adopted here, and are incorporated in the costs of MOX fuel manufacture. Where plutonium passes internally from a reprocessing plant to a store or to fabrication plant on the same site the costs are trivial.

2.5.4.13 Spent Fuel Disposal

There is still a great deal of uncertainty about the costs of long term storage of spent fuel or radioactive wastes, of their conditioning and of their final disposal. Costs will depend on geology, storage times, scale of operations etc. There are as yet no disposal facilities in operation and there is no commercial activity in this general area. Fairly wide ranges were adopted in the previous study (4) but this had little impact on the overall levelised costs of the nuclear fuel cycle, although it could have a bigger effect on the relative costs of alternative fuel strategies.

There will be no fundamental difference in the disposal costs for uranium or MOX fuel, although both are considered to be higher than the disposal costs of equivalent vitrified fission product wastes which have a significantly smaller volume and lower long term heat output.

There are some who believe that waste conditioning and disposal costs (spent fuel and fission products) are likely to rise relative to past perceptions as the practical aspects are tackled, in much the same way as has been experienced with reactor investment and reprocessing in the past. Because of discounting this would not greatly influence overall fuel cycle costs but it could affect MOX - UO_2 fuel differentials. In general a country that has opted to recycle plutonium would not be expected to want to dispose of MOX fuel unless the plutonium had become so isotopically degraded as to be useless in thermal reactors. This situation can be avoided by constantly mixing multiply recycled plutonium with fresh material. Alternatively the fuel that is of little use in thermal reactors could be saved for use in fast reactors where its energy worth (Section 2.4.6) is higher.

No specific cost projections have been produced for this study and no values are recommended in view of the impending detailed examination of this topic by another NEA expert group.

2.5.4.14 Trends in Costs

The likely trends in costs have been discussed briefly in the preceding sections dealing with specific parts of the fuel cycle. Apart from uranium prices, where re-establishment of an equilibrium market and resource depletion are expected to lead to stable though higher prices in the medium term and rising prices in the longer term, costs of most parts of the fuel cycle should remain stable or decline. The three factors contributing to downward pressure on prices are technological development, benefits of scale and commercial competition.

Events that could upset this trend would be a requirement for even more stringent safety or radiation exposure standards or the imposition of even more demanding safeguards monitoring and surveillance techniques. Because the design standards for future back-end plant and stores already incorporate very tight specifications for release of radioactivity to the environment in routine operation, as well as monitoring and accounting procedures to meet International Safeguards requirements, those planning to operate them see no reason to ancitipate significant cost escalation from these causes.

Costs in constant US $ terms may appear to change in the future if the relative values of currencies change - thus uranium dioxide fabrication costs which were comparable in the US and Europe in the mid-1980s have apparently diverged because of the considerable decline in the value of the US $ relative to European currencies (specifically the ECU). Table 13 gives exchange rate values for January 1984 and January 1987. This does create problems when looking to the future and contributes to differences of national perceptions about the economic attractiveness of different options.

2.6 Fuel Cost Illustrations and Sensitivities

2.6.1 Introduction

The illustrations in this section are simplified examples to bring out specific aspects of plutonium use. They are based mainly on plutonium produced in PWRs from 33 000 MWd per tonne burn-up uranium oxide fuel. The spent fuel is assumed to be stored for 4 or 10 years prior to reprocessing and MOX fuel assemblies are assumed to be loaded into the reactor two years after plutonium recovery. Figure 16 shows the leads and lags in the uranium and MOX fuel cycles. MOX fuel is assumed to be produced using depleted uranium containing 0.225 per cent uranium-235.

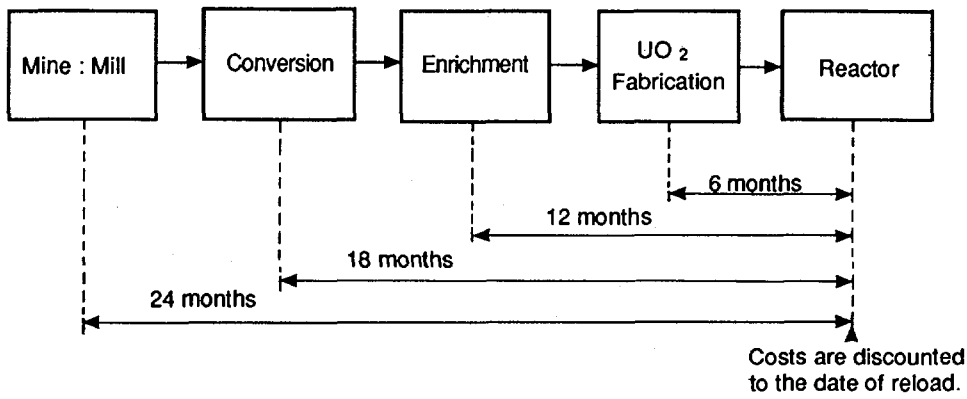
Because MOX fuel will not be in widespread use before the mid-1990s, the uranium fuel for non-MOX fuelled PWRs with which it will be competing is likely to have higher burn-up: 43 000 MWd per tonne and 53 000 MWd per tonne uranium oxide fuels have therefore been considered. The possibility of higher burn-up MOX fuel cannot be excluded either so the calculations have also been performed for these although the plutonium in the illustrative cases is assumed to come from 33 000 MWd per tonne uranium oxide fuel since lags in reprocessing mean that this is likely to be the case up to the year 2000. Sensitivities are provided for the use of plutonium from higher burn-up uranium fuels.

As indicated earlier (Section 2.2), in the 1990s the MOX will in general be fed into reactors which have already been operating for some time on uranium fuel. The calculations have therefore been confined to this case and relate to equilibrium fuel charges in which MOX substitutes for enriched uranium oxide fuel in 30 per cent of the core.

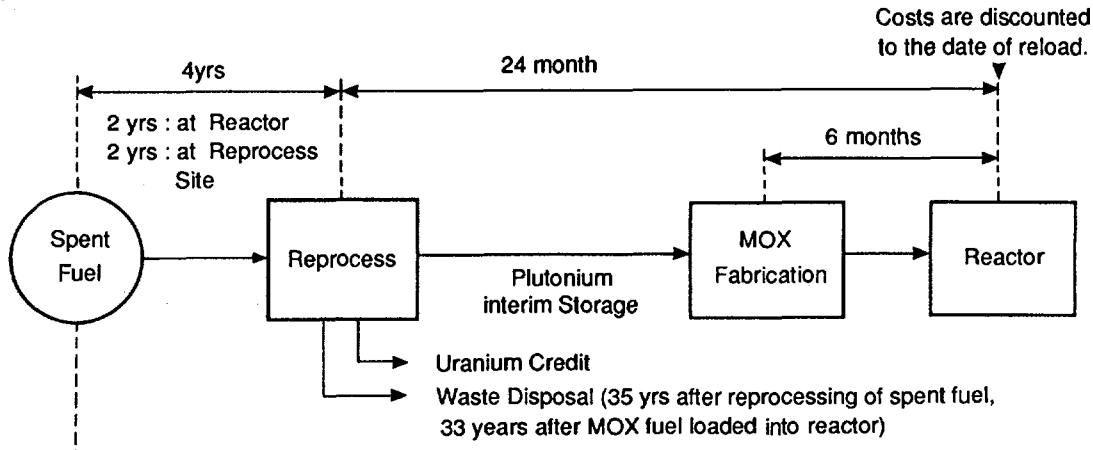
The fissile materials logistic calculations on which the costs are based were performed by Belgonucléaire using a specific common PWR to ensure that the data were on a consistent basis (Annex C). The cost calculations were undertaken by PNC, Japan. They are based on the unit cost ranges set out in Table 14. Since most of the sensitivities to changes in cost assumptions are simple linear functions, the fuel costs associated with different assumptions about individual stage costs, including those for the base case described in Section 2.4 can be derived by interpolation or extrapolation.

Figure 16. **LEAD AND LAG TIMES**

a) Uranium Fuel Front - end lead times



b) Reprocess and Recycle



c) Spent Fuel Disposal

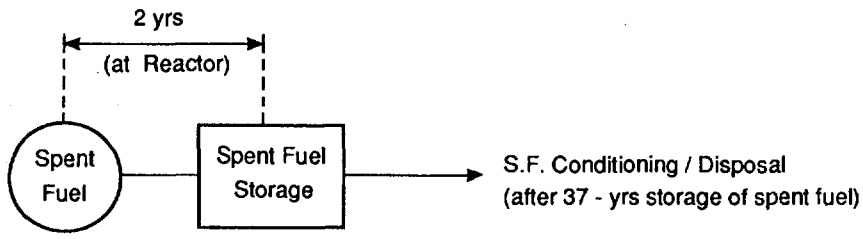


Figure 17. **ILLUSTRATIVE COSTS PER KG FOR EQUILIBRIUM REPLACEMENT PWR FUELS (USING FREE PLUTONIUM)**

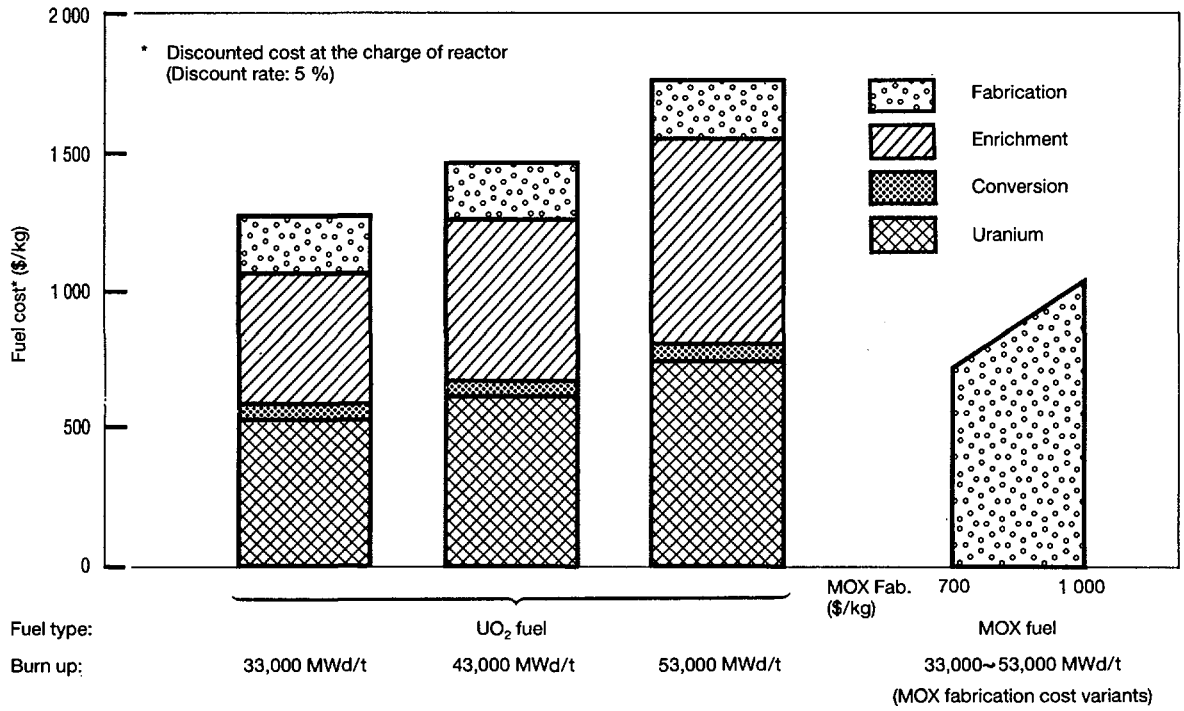
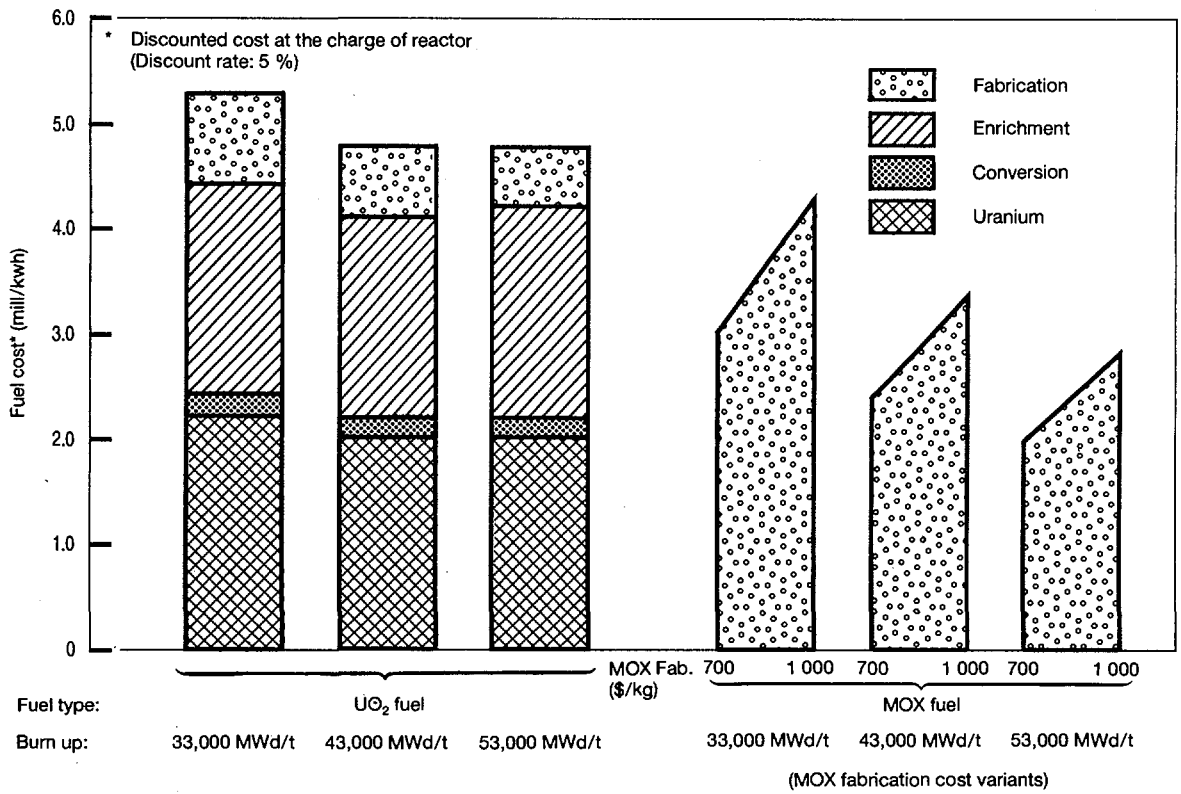


Figure 18. **ILLUSTRATIVE COSTS PER KWH FOR EQUILIBRIUM REPLACEMENT PWR FUELS (USING FREE PLUTONIUM)**



2.6.2 Cost Comparisons

The MOX fuel costs presented in this section are based on two alternative assumptions. The first case is that the plutonium used has already been separated and paid for by the utility as part of its contract for reprocessing services or the utility is committed to its separation for contractual or policy reasons. In this case plutonium recovery costs are sunk and the plutonium is free so far as some utilities and countries are concerned: i.e. it is ascribed a zero monetary value. This assumption applies for existing stockpiled plutonium.

The second case looks at MOX produced using plutonium that would not otherwise have been recovered. It prices plutonium at its full recovery cost, i.e. the net costs of reprocessing spent uranium oxide fuel allowing credit for the uranium recovered. This case applies for some countries which have no pre-existing committment to spent fuel reprocessing. Annex H gives details of the calculation methods and develops a simple formulation illustrating the comparative economics of MOX and UO_2 fuels.

All fuel costs are discounted or compounded to the time of charging fuel into the reactor using a 5 per cent discount rate with a sensitivity variant of 10 per cent.

2.6.2.1 Case A - Free Plutonium (recovery costs sunk)

The costs of producing 1 kg of fuel from fresh natural uranium and from MOX using depleted uranium are illustrated in Figure 17 based on the illustrative unit process costs set out in Table 14. The MOX fuel cost is independent of the desired burn-up for this free plutonium case since the MOX fuel fabrication cost is independent of its plutonium content within reasonable limits. The uranium used in MOX fuel is depleted enrichment plant tails stored as the hexafluoride so that it too is free. The uranium oxide fuels differ for different burn-ups due to the differing levels of enrichment and natural uranium required.

With free plutonium, MOX PWR fuel will be, for the base case significantly cheaper per kg than fresh uranium fuel and this would be equally true if recycled unenriched or natural uranium were used for MOX fabrication in place of the depleted uranium adopted for Figure 17.

It should be noted that the cost per kg does not take account of the energy that will be obtained from the fuel. The fuel cost per unit of energy output is presented in Figure 18. MOX fuel from free plutonium is cheaper per unit of energy output for each design burn-up with the base case or with the higher or lower uranium fuel fabrication costs to which fuel costs are not very sensitive (Table 15). This comparison can be judged appropriate since reactor operators will want to substitute MOX for uranium fuel of similar burn-up for simplicity. There is also the possibility in the earlier years that MOX will be used in reactors operating with lower burn-up uranium fuels while higher burn-up uranium oxide fuels are used in different reactors. Even here the MOX with free plutonium appears to have an advantage although this advantage is reduced or may be eliminated when the whole reload is considered due to differences between the costs of the 70 per cent of uranium oxide fuel in the core (Figure 22).

Figure 19 illustrates the sensitivity of fuel costs to the main parameters uranium price, separative work costs and MOX fabrication costs. In the mid-1990s the MOX fabrication costs may still be relatively high ($800-$900 per kg) but, with separative work costs still likely to be $100 per SWU. MOX fuel at these costs looks attractive at uranium prices down to well below $50 per kg U. As MOX fabrication costs decline its advantage will increase even if separative work costs decline.

Figure 19. **SENSITIVITY OF FUEL COSTS TO URANIUM PRICE, SWU COSTS AND MOX FABRICATION COSTS (USING FREE PLUTONIUM). ASSUMED BURN UP IS 33,000 MWd/t.**

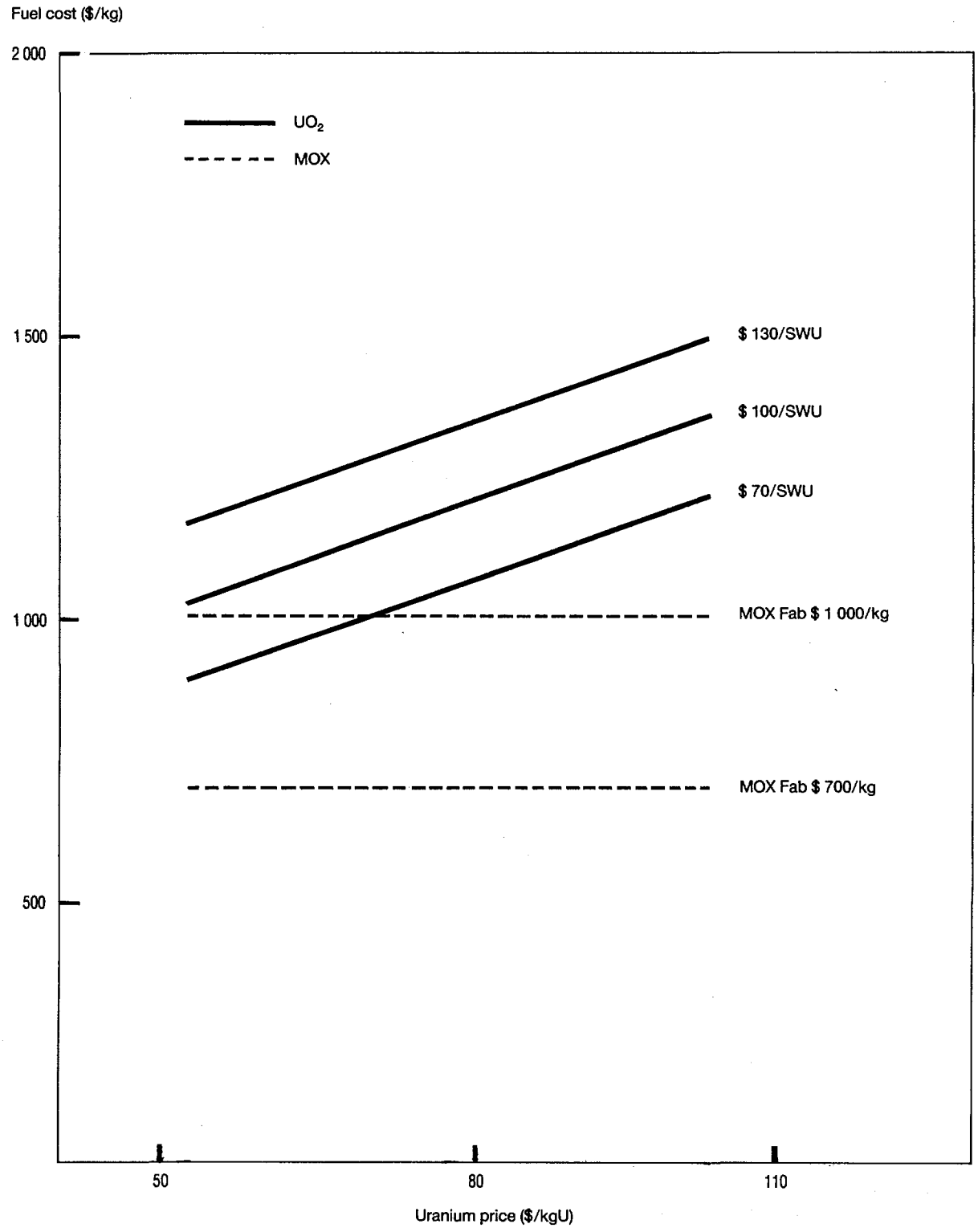
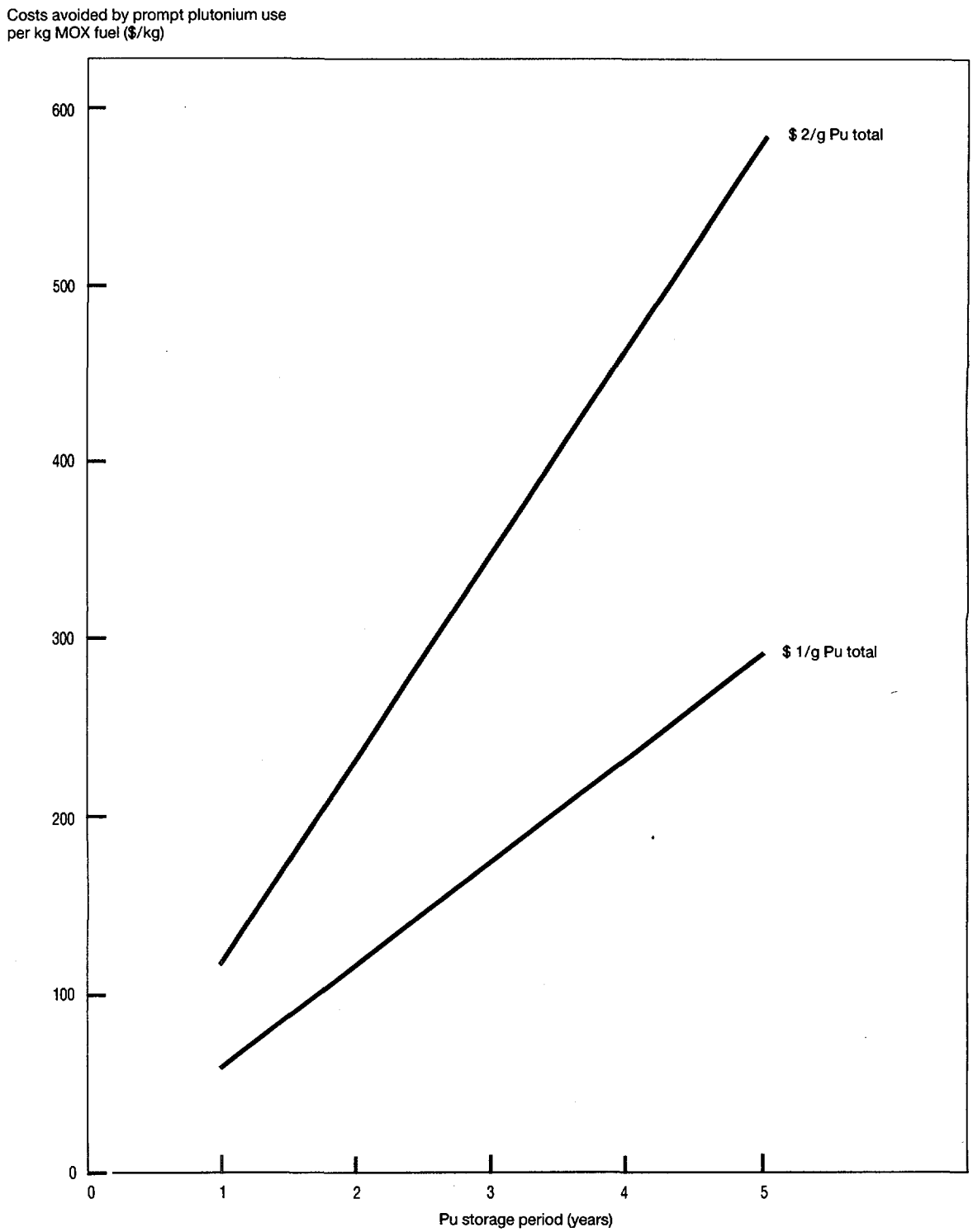


Figure 20. **AVOIDED PLUTONIUM STORAGE COSTS FOR 33,000 MWd/t LWR FUEL**



NB: Americium removal, if necessary, will add $ 1 200/kg to fuel costs depending on process costs.
Decay of plutonium also affects costs/kg fuel due to decay of fissionable isotopes (Figure 7 and Table 6).

This clear advantage to MOX replacement fuel batches for countries with existing plutonium stockpiles is reinforced by their avoidance of plutonium storage costs, which are not negligible (Figure 20), and americium removal costs if these become necessary. It should be noted however that whilst there are savings in fresh fuel manufacture it is at the cost of tying up the separated plutonium once again in spent fuel which itself will have to be reprocessed if the plutonium is wanted for further recycle in thermal or fast reactors. On the other hand more plutonium can be recovered than from uranium fuels. The costs per kg HM of the back-end of the fuel cycle for MOX will be little different, however, from those of reprocessing the corresponding uranium fuel so that this will not be seen as an additional cost by countries whose policy is to reprocess all spent fuel.

2.6.2.2 Case B - Plutonium charged at recovery cost

In circumstances where there is no plutonium stockpile and it is not considered imperative to reprocess the spent fuel, the availability of plutonium for use in MOX will be limited to material specifically recovered for recycle.

In such a case the costs of reprocessing and conversion of the plutonium to oxide would be an additional charge to the MOX fuel, offset by any savings on spent uranium fuel storage charges and any credit for the recovered uranium, taking due account of any difference in the conditioning and disposal costs of spent fuel and reprocessing wastes (Section 2.5.4.9). Allowance should also be made for the value of residual plutonium and uranium in spent MOX fuel after deducting their recovery costs. This has however been ignored in this study since multiple recycle in LWRs is unlikely to be significant before the year 2000, by which time it may be preferred to store the plutonium for use in fast reactors; and this would change its value. Annex H, Section 4.2 demonstrates that reprocessing specifically to recover plutonium for thermal recycle becomes economic if the differential cost between reprocessing, including conditioning, storage and disposal of reprocessing wastes ($e per kg HM) and spent fuel storage, conditioning and disposal ($d per kg HM) both with appropriate discounting, were less than the value attached to recovered plutonium ($f) and uranium ($g), both per kg HM of reprocessed fuel, also appropriately discounted. Specifically, using the symbols defined in Annex H, where j is the discount factor ($j = 1 + r$, with r the discount rate), when: $f + g > (e - d)j^2$. The former credit is shown (Annex H, Table H.9) to be sensitive to uranium price, MOX fabrication and separative work costs.

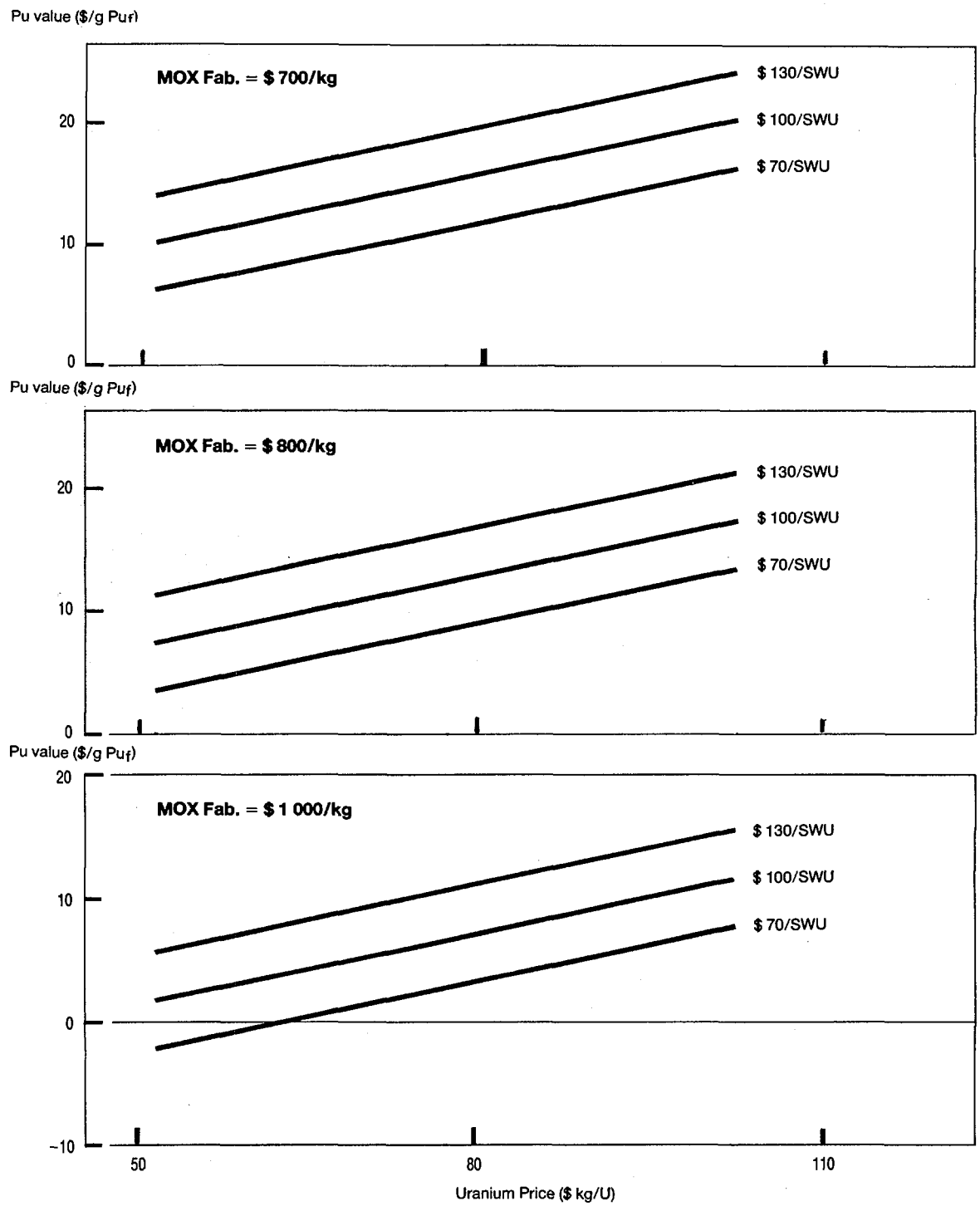
As explained earlier no fresh evaluation of spent fuel storage or spent fuel or reprocessing waste conditioning and disposal costs was undertaken for this study (Sections 2.5.4.7, 2.5.4.9 and 2.5.4.13) and there is uncertainty about their likely future value. Whilst this is not highly significant for overall nuclear fuel costs, small differences could be important for the relative costs of reprocessing and once through cycles, and a forthcoming study of storage and repository costs is expected to provide up-to-date evidence on these important cost elements.

The range of credits (f + g) calculated for the cost ranges adopted for illustration in this study are tabulated in Table H.9 and run from around $129 to $245 per kg HM of uranium oxide fuel for once-through MOX cycles and 33 000 MWd per tonne fuels with uranium at $80 per kg U. This would require the discounted reprocessing, waste conditioning and disposal costs to be no more than around $117 to $222 per kg HM higher than the discounted spent fuel storage, conditioning and disposal costs.

The range would be expanded if other uranium prices were considered. The reference differential e - d in the previous study (4) in 1984 US $ was $450 per kg HM with a maximum range of $110 per kg (minimum reprocessing, maximum fuel storage) to $1000 per kg (maximum reprocessing, minimum fuel storage). The importance of having reliable values for both reprocessing waste and spent fuel storage, conditioning and disposal costs is made clear in the context of this study.

If MOX is produced from a mixture of spent MOX and uranium fuels or if different burn-ups are planned, the plutonium and uranium credits will differ due to the different plutonium yields and initial and final isotopic compositions. Other factors having an influence include the phasing of fuel cycle stages which can alter the values attached to recovered plutonium and uranium, both due to the effects of discounting and due to radioactive decay of the plutonium.

Figure 21. **SENSITIVITY OF PLUTONIUM INDIFFERENCE VALUE TO ENRICHMENT PRICE AND MOX FABRICATION COSTS***
(Fuel Burn up: 33,000 MWd/t)



* The diagrams show the variation of the dollar value of 1 g plutonium in MOX/fuel for 33 000 MWd /t burn up in comparison to an equivalent amount of enriched uranium (to produce the same quantity of energy) in uranium fuel for the same burn up, depending on the price of natural uranium, on costs of enrichment services (per SWU) and on MOX fabrication costs.

The co-processing of MOX and uranium fuels will enhance the value of plutonium and increase the break-even costs differential (e-d) compared with the quantitative illustration summarised above. Conversely, delays in reprocessing or plutonium utilisation will reduce plutonium and uranium credit values and consequently reduce the break-even differential although this could be offset if the front-end costs of uranium cycle were rising.

2.6.3 The Effect of MOX Fuel Burn-Up

Whereas for free plutonium (Section 2.6.2.1) the plutonium content of the equilibrium MOX fuel batch has no influence on the latter's costs, the same is not true when the MOX fuel is charged with plutonium recovery costs.

The higher uranium-235 enrichment needed for the higher burn-up uranium fuels involves higher feed uranium and enrichment costs and calls for larger quantities of plutonium in the replacement MOX (Table 12). For fuels of equivalent burn-up the substitution value of plutonium increases and the plutonium credit per kg of fuel reprocessed (f) increases as the required burn-up increases, i.e. MOX and reprocessing are more attractive as higher burn-ups are sought. The necessary calculations can be done using Tables H.4 and H.8 of Annex H.

2.6.4 Plutonium Decay

Because plutonium decays over time its energy worth in thermal reactors also decreases (Figure 7). This increases the effective recovery costs per unit of plutonium energy worth and increases the MOX fuel cost in those cases covered in Section 2.6.2.2.

Once the spent fuel is reprocessed, regardless of the storage cooling times before reprocessing, it is important that the Pu be fabricated into MOX fuel assemblies relatively soon to avoid additional fuel fabrication costs due to build up of high energy gamma ray emitters in the Pu over time after reprocessing. This gamma activity derives from build up of americium-241 plus the daughter products of Pu-236 in the plutonium. This fabrication cost penalty will not be significant, in itself, if and when automated, shielded hands-off fabrication facilities become available in the future. Americium-241 is also to be avoided due to its adverse neutron absorption characteristics (Table 5).

2.6.5 Indifference Values

An alternative way of looking at the same data is in terms of the plutonium indifference value. This was defined in our earlier study (4) as the value that plutonium would have to have to make the costs of uranium oxide fuel (including reprocessing costs, but deducting the value of recovered uranium and plutonium), equal to the costs of MOX fuel. For this study focussed mainly on the 1990s the indifference value has been related solely to front-end fuel costs on the assumption that back-end costs for uranium and MOX fuels will be similar. Figure 21 shows how this plutonium value varies with enrichment cost, uranium price and MOX fabrication cost for the 33 000 MWd per tonne uranium and MOX fuels. (See Annex H for further details of the calculations).

2.7 Other Sensitivities

2.7.1 Uranium Sources

2.7.1.1 With "free" plutonium

With free plutonium the cost per kg of MOX fuel is the fabrication cost plus the price paid for any uranium used - the higher the U-235 content of this uranium the less "free" plutonium is required in the fuel mix.

If depleted uranium from enrichment plant tails is used then this uranium too is effectively "free" and the fuel cost is thus the fabrication cost alone since any conversion costs are covered in the cost of fabrication as defined here. While the use of recovered uranium in MOX fuel requires no additional handling precautions, it affects the availability of reprocessed uranium to be recycled directly. The potential extra costs due to supplementary handling precautions in conjunction with direct recycling via re-enrichment of reprocessed uranium could be reduced substantially through blending with natural uranium. If only natural uranium is used with "free" plutonium there is an overall cost increase of about 10 per cent (with uranium at $80 per kg U) to the total front-end cost of MOX fuel: such an increase does not undermine the economic case for free plutonium MOX fuel.

The use of recycled LWR uranium in MOX fuel saves plutonium and will enable larger quantities of MOX fuel to be produced from a given plutonium stock. It therefore increases the attainable cost savings.

2.7.1.2 Plutonium charged with recovery costs

When the plutonium used has to pay for its own recovery the situation changes.

The substitution of natural or reprocessed uranium for depleted uranium results in a cost reflecting their market value and equivalent worth respectively. However, in this case there is an economic benefit in substituting uranium recovered from reprocessing, with its higher U-235 content (0.92 per cent), in place of natural uranium with a lower U-235 content (0.71 per cent), or depleted (0.225 per cent), since the use of a higher U-235 content uranium decreases the amount of fissile plutonium required in the MOX fuel and hence the quantity of spent fuel needing to be reprocessed to recover it. This would result in lower specific recovery costs per gram equivalent worth of fissile material to be used in MOX fuel and would leave about two thirds of recovered uranium for recycle as UO_2 fuel after enrichment. Section 4.2 of Annex H shows that the credit value of recovered PWR uranium, based on re-enrichment and recycle in uranium fuel, is equaly recoverable by use of the slightly enriched uranium to save plutonium in MOX fuel.

2.7.2 Discount Rates

The effect of "discounting" fuel costs in the way done in this study is to increase them by effectively adding interest at 5 per cent compound p.a. to the expenditures prior to fuel going into the reactor. A higher rate of discount will accentuate the differences identified in previous sections and make the MOX with free plutonium case look more attractive (Table 16) and the high recovery/fabrication cost plutonium worse relative to ordinary uranium oxide fuels. The effect is not however large for the fuel cycle lead times adopted in this report.

Table 16

EFFECT OF DISCOUNT RATE ON COSTS PER KWH
FOR REPLACEMENT FUELS USING FREE PLUTONIUM

Discount Rate	Burn-up (MWd/t)	Fuel Cost* (mills/kWh)		Difference (mills/kWh) (1) - (2)
		UO2 fuel (1)	MOX fuel (2)	
5 %	33 000	5.25	3.41	1.84
	43 000	4.73	2.68	2.05
	53 000	4.72	2.22	2.50
10 %	33 000	5.98	3.73	2.25
	43 000	5.51	2.99	2.52
	53 000	5.62	2.54	3.08

* MOX fuel costs based on $800 per kg of MOX fabrication cost.

2.7.3 Uranium Dioxide Fabrication Costs

The costs of uranium dioxide fuel fabrication differ between countries (Section 2.5.4.5) but the savings attached to MOX fuel use are not greatly affected by this parameter. (Table 15 shows the sensitivity for the free plutonium case.)

2.7.4 Plutonium from Higher Burn-up Fuels

Plutonium recovered from 43 000 MWd per tonne uranium fuel is higher in quantity but has a lower fissile content (per cent) than that from 33 000 MWd per tonne fuel (Table 9). The net effect is to increase its fissile worth per kg of uranium fuel reprocessed. It follows from Tables H.4 and H.8 (Annex H) that the value of plutonium recovered per kg of UO_2 fuel reprocessed is higher and MOX use becomes more economically attractive.

2.8 Fuel Reloads and Systems Savings

The costs in the previous section all relate to MOX replacement fuel. In existing PWRs the MOX fuel can only replace 30 per cent of the uranium fuel so that the saving or extra cost per reload is proportionately diluted.

The reload costs for enriched uranium and MOX fuel are illustrated for 33 000 MWd per tonne, 43 000 MWd per tonne and 53 000 MWd per tonne in Figures 22 (Table 17) and 23 (Table 18). The figures take plutonium and depleted uranium costs as zero. The replacement fuel batch is taken to be 24 tonnes for 33 000 MWd per tonne fuel, 18.5 tonnes for 43 000 MWd per tonne and 14.8 tonnes for 53 000 MWd per tonne corresponding to one third, one quarter and one-fifth annual core reloads (Annex H, Section 6).

Figure 22. **ECONOMIC COMPARISON OF RELOAD COSTS, USING FREE PLUTONIUM (DISCOUNT RATE = 0 %)**
For back up data see Table 17

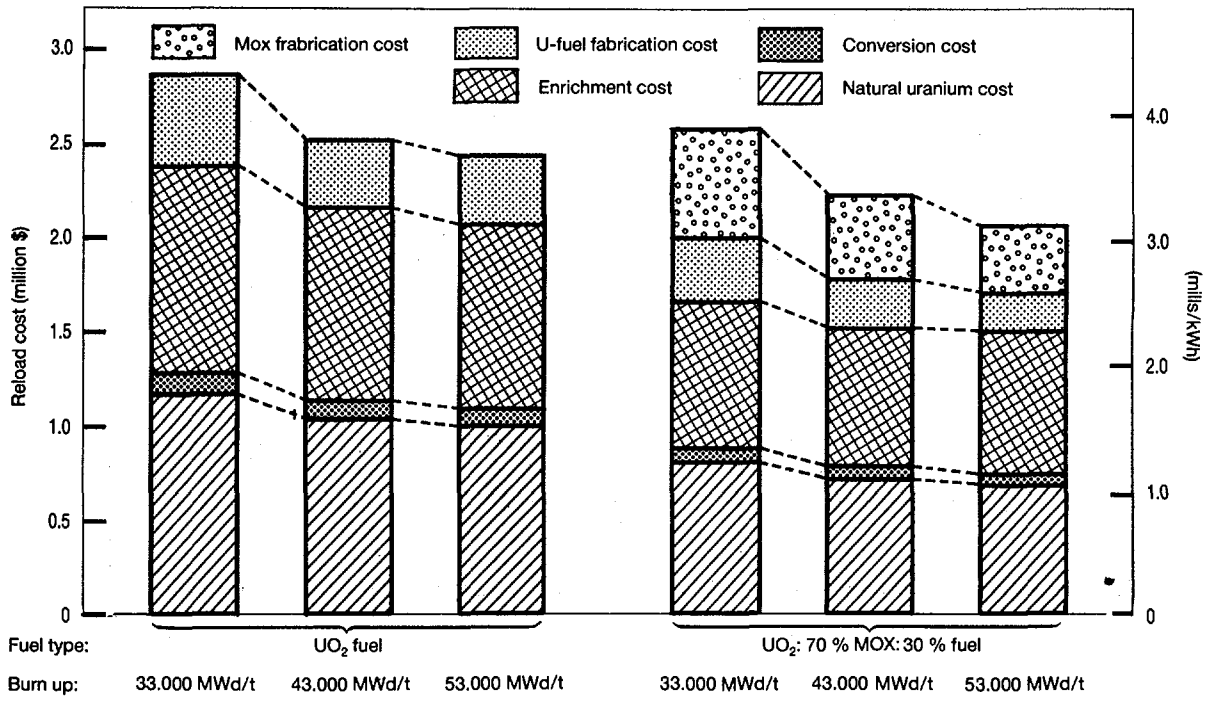
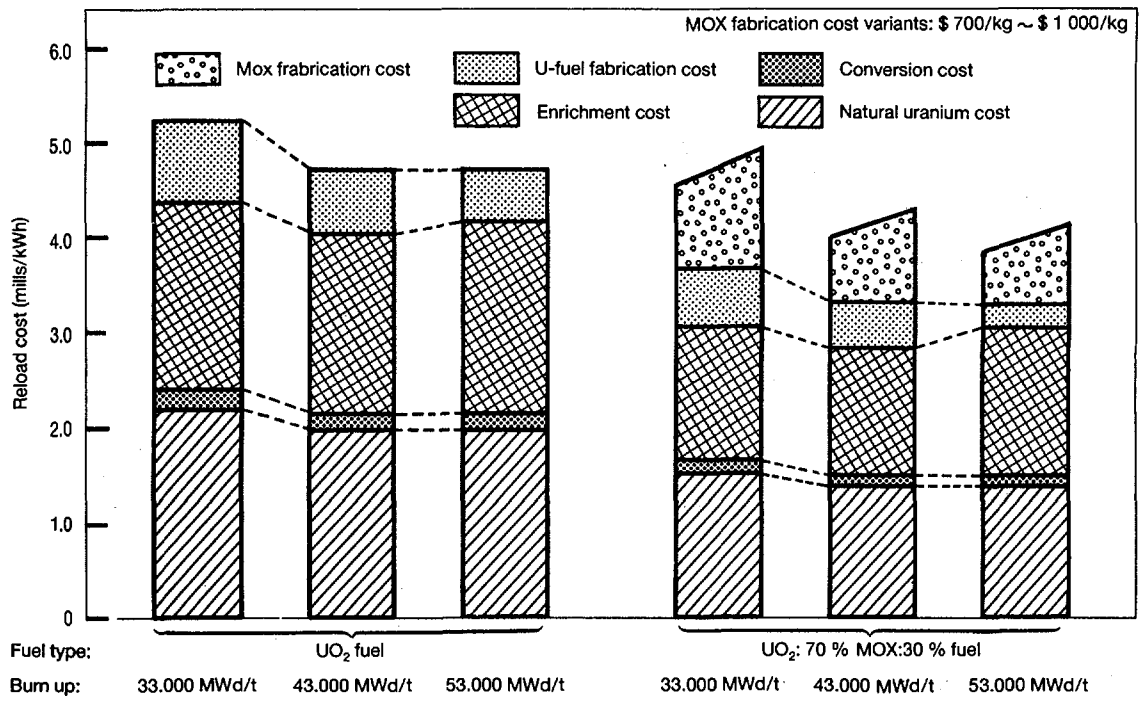


Figure 23. **ECONOMIC COMPARISON OF RELOAD COSTS, USING FREE PLUTONIUM (DISCOUNT RATE = 5 %)**
For back up data see Table 18



The MOX/UO_2 reload is shown for both \$700 and \$1000 per kg MOX fabrication costs in Figure 23 and Table 18. The batch reload savings (with free plutonium) range from around \$3 M to \$4 M for the \$80 per kg uranium case with equal uranium oxide and MOX fuel burn-up. However on a unit energy produced basis (i.e. per kWh) there is little difference between 43 000 MWd per tonne or 53 000 MWd per tonne uranium oxide fuel and a 33 000 MWd per tonne MOX/UO_2 reload with uranium at \$80 per kg.

The costs of fuel for reactors fuelled throughout their lives with MOX can be calculated using the appropriately adjusted initial and final discharge fuel enrichments. Such a calculation is not particularly useful at this time since utilities are faced with decisions on individual fuel batches not on the relative attractions of PWRs with one or other fuel cycle, although it should be remembered that reloading frequency can affect reactor output and that there are smaller quantities of higher burn-up fuels requiring subsequent storage and reprocessing.

The comparisons made here on the basis of front-end costs are satisfactory in principle for answering the question about use or non use of plutonium stocks. However they are not directly comparable with the costs published in the literature for average reactor fuel costs (4) since neither the uranium nor the MOX fuel costs include charges for dealing with spent fuel.

The data contained in Section 2.5 and the full methodology described in reference 4 will permit approximate calculations of total lifetime fuel cycle costs using natural or reprocessed uranium, or MOX should this be desired.

2.9 Other Factors Affecting Fuel Cycle Choice

2.9.1 Introduction

Sections 2.2 and 2.3 of this report described the options for plutonium use or non-use and the technical considerations that could influence decisions on which option to pursue. Sections 2.4 and 2.5 have looked at the logistics and economics of plutonium recycle in thermal reactors.

This section briefly describes the wider considerations that governments and utilities will wish to take into account in reaching decisions on whether to use plutonium and if so on how and when to use it. As indicated earlier governments will continue to attach importance to non-proliferation and the application of international safeguards in formulating their fuels policies.

2.9.2 Strategic Factors

The choice of fuel cycle can have important implications in terms of the dependence of a country on external sources of fuel supply. The move away from oil as a fuel for electricity generation has greatly reduced the vulnerability of most western nations to supply disruptions arising from political events outside their control.

However, for many countries, the switch from oil to natural gas or to coal and/or uranium, has made them dependent on imports of these fuels, and, in the case of uranium, on enrichment and fuel fabrication services provided by other countries. At the present time there appear to be no risks of major disruption in these latter markets; nevertheless there have been isolated supply problems in the past linked to changes in the policies of the governments of supplier countries. The situation could become more difficult for uranium in the longer term future as resources are depleted or as the world becomes more dependent on its use as a fuel.

Table 17
(Back-up Table for Figure 22)

ECONOMIC COMPARISON OF RELOAD COSTS, USING FREE PLUTONIUM
(Discount Rate 0 %)

	I Enriched uranium fuel		
Burn-up:	33 000 MWd/t	43 000 MWd/t	53 000 MWd/t
Natural Uranium			
Quantity (tonnes):	150	133	128
Cost (Million $)	11.7	10.4	10.0
Conversion			
Quantity (tonnes):	150	133	128
Cost (Million $)	1.1	0.9	0.9
Enrichment			
Quantity (TSWU)	111	103	105
Cost (Million $)	11.1	10.3	10.5
U-Fuel Fabrication			
Quantity (tonnes):	24	18.5	14.8
Cost (Million $)	4.8	3.7	3.0
TOTAL COST (Million $)	28.7	25.3	24.4

	II Mixed Oxide (MOX) Fuel		
Burn-up:	33 000 MWd/t	43 000 MWd/t	53 000 MWd/t
Natural Uranium			
Quantity (tonnes):	105	93	89
Cost (Million $)	8.2	7.3	7.0
Conversion			
Quantity (tonnes):	105	93	89
Cost (million $)	0.7	0.7	0.6
Enrichment			
Quantity (TSWU)	77	77	74
Cost (Million $)	7.7	7.2	7.4
U-Fuel Fabrication			
Quantity (tonnes):	16.8	16.8	10.4
Cost (Million $)	3.4	2.6	2.1
MOX Fuel Fabrication			
Quantity (tonnes):	7.2	5.5	4.4
Cost (Million $)	5.8	4.5	3.6
TOTAL COST (Million $)	25.8	22.3	20.7

Table 18
(Back-up Table for Figure 23)

ECONOMIC COMPARISON OF RELOAD COSTS, USING FREE PLUTONIUM
(Discount Rate 5 %)

	I Enriched uranium fuel		
Burn-up:	33 000 MWd/t	43 000 MWd/t	53 000 MWd/t
Natural Uranium			
Quantity (tonnes):	150	133	128
Cost (mills/kWh)	2.21	1.99	1.99
Conversion			
Quantity (tonnes):	150	133	128
Cost (mills/kWh)	0.19	0.18	0.18
Enrichment			
Quantity (TSWU)	111	103	105
Cost (mills/kWh)	1.98	1.89	2.00
U-Fuel Fabrication			
Quantity (tonnes):	24	18.5	14.8
Cost (mills/kWh)	0.86	0.66	0.56
TOTAL COST (mills/kWh)	5.24	4.72	4.73

	II Mixed Oxide (MOX) Fuel		
Burn-up:	33 000 MWd/t	43 000 MWd/t	53 000 MWd/t
Natural Uranium			
Quantity (tonnes):	105	93	89
Cost (mills/kWh)	1.54	1.40	1.40
Conversion			
Quantity (tonnes):	105	93	89
Cost (mills/kWh)	0.14	0.12	0.12
Enrichment			
Quantity (TSWU)	77	77	74
Cost (mills/kWh)	1.39	1.33	1.40
U-Fuel Fabrication			
Quantity (tonnes):	16.8	16.8	10.4
Cost (mills/KWh)	0.6	0.47	0.38
MOX Fuel Fabrication			
Quantity (tonnes):	7.2	5.5	4.4
Cost (mills/kWh)*	0.89 1.28	0.70 1.00	0.58 0.84
TOTAL COST (mills/kWh)	4.56 4.95	4.02 4.32	3.88 4.14

* The left hand number in each column corresponds to the low cost MOX fabrication variant of $700 per kg and the right hand number with the high cost variant of $1000 per kg.

For this reason, in addition to any technical or economic considerations, some countries see advantages in reducing dependence on fuel imports through the more efficient use of uranium. This greater material efficiency can be achieved in several ways:

(a) By increasing utilisation of fuel in existing reactors;

(b) By recovering remaining fissile and fertile materials from spent fuel and making use of them;

(c) By using fertile material stockpiles arising from uranium enrichment (the depleted uranium tails);

(d) By using fertile thorium through the thorium/uranium cycle.

Work on getting higher fuel burn-up in existing reactors is in progress in many countries. There will in general be an economically optimum burn-up level which will be determined partly by the costs of uranium, separative work and fuel fabrication, partly by any reductions in reactor operating costs achieved by reducing the downtime associated with refuelling, and partly by savings in the costs of the back-end of the fuel cycle which result from reduced fuel throughput. Fuel burn-up is generally arranged to synchronise with annual system load cycles so that off-load reactor refuelling takes place at periods of low demand at 12 or 18 month intervals. The economically optimum burn-up will not theoretically be the most efficient in terms of natural uranium utilisation but experience has shown that it is very close. This is understandable considering the large influence of uranium prices on fuel cycle costs (see for example Figure 18).

Other routes to increasing uranium utilisation in reactors include core fuel management and the achievement of higher conversion ratios.

The recycling of uranium and/or plutonium recovered from spent fuel has been described in detail in the earlier parts of this report. It can decrease natural uranium requirements by some 10-15 per cent with uranium recycle and a further 20-25 per cent by recycling plutonium, both in thermal reactors (33 000 MWd per tonne burn-up). Use in fast reactors could ultimately reduce uranium requirements to one-fiftieth or less for equivalent energy outputs.

The uranium-235 left in enrichment tails has amounted to over one-third of the initial content of the natural uranium feedstock. The tails level (historically 0.25 per cent to 0.3 per cent) has been determined by the relative costs of uranium and separative work. With the advent of lower cost enrichment technologies the optimum tails assay has declined and with advanced centrifuges and lasers it could become economically worthwhile to strip more uranium-235 from the existing stockpiles of depleted uranium. The choice would depend on the price and availability of fresh uranium feedstock. Alternatively the tails could be used in MOX fuel or in a fast reactor breeder blanket.

The final option, (d), has been the subject of research in several countries in connection with heavy water moderated reactors and high temperature reactors. In OECD countries interest to date has focussed on the potential for thorium to breed uranium-233 which can be burnt in situ, thus increasing the energy output from batches of fuel. Cycles of this type can in theory achieve high uranium conversion efficiencies (31). The use of plutonium in thorium fuel cycles has been described in Section 2.4.7.

The choice of fuel cycle can have both shorter and longer term effects on the efficiency of uranium utilisation. Cycles devised to extract the maximum energy from uranium in a single passage of fuel through a thermal reactor can reduce the energy recoverable by subsequent recycling of residual fissile materials. This may be preferred by a country committed to the once-through mode of fuel use, or which is seeking economies in the short to medium term. There is relatively little long term strategic advantage to be gained however from the reductions in uranium requirements associated with

higher burn-up or plutonium recycle. The ability to operate plant without importing uranium can only come from adoption of fast breeder reactors or, in countries with indigenous economically recoverable thorium deposits, through thorium converters.

The consumption of plutonium in thermal reactors via recycle or higher in situ burn-up would reduce the quantities available to launch a breeder reactor programme in the very near future. This could slow the latter's penetration into the electricity system in the short term, but would not affect significantly the total energy recoverable from a country's uranium stocks in the long term. It would however affect both the rate of penetration and the total energy recoverable from thorium converters.

Countries' attitudes will differ depending on whether they have large indigenous stocks of natural uranium, enrichment tails, spent fuel, plutonium or thorium minerals and on their perceptions of future fuel markets and their stability, as well as on the economic and technical attractions of the alternatives.

The different options are not mutually exclusive and operate on different timescales. The independent ability to use MOX fuel or recycle uranium tails may help to alleviate temporary crises in fuel supply. Fast reactors on the other hand will only be effective when they are in place and supplying the bulk of a country's electricity, since they will take many years to plan, construct and commission.

2.9.3 Ecological Factors

The substitution of recycled plutonium and uranium for natural uranium in PWR fuel can reduce uranium requirement by 30 per cent to 40 per cent (Section 2.9.2) and this has environmental benefits since it reduces the need for mining and the quantities of mill tailings whilst also reducing the radiation exposure of workers and the public associated with mining and milling operations.

The procedures for controlling and managing mining and waste disposal operations have to conform to the same high standards with or without recycling but the reduced quantities should help to reduce overall costs in the recycling option.

Furthermore the removal of uranium and plutonium and other long-lived alpha-emitters from spent fuel for recycling reduces the level of long-lived radioactivity that has to be disposed of.

Reprocessing spent fuel does however result in the release of gaseous and liquid radioactive effluents to the environment. It also creates additional volumes of low and intermediate radioactivity level contaminated wastes compared with the direct disposal of unprocessed spent fuel, although the volume of high activity wastes is reduced by a factor of around two and a half.

The ecological/environmental implication of these alternatives are beyond the scope of this study but detailed examinations of the alternatives can be found in the literature (43).

2.9.4 Institutional Factors

There are several important non-technical factors that have to be taken into consideration by utilities contemplating the use of MOX fuels.

Perhaps the most important of these for many countries will be the nature of the constraints or restrictions imposed on plutonium recycle by the original suppliers of the feed uranium, the separative work or the fabricated fuel. A number of supplying countries, in order to strengthen international controls on potential weapons usable materials, have included conditions that prohibit recycle without prior mutual agreement.

Subject to such contractual arrangements a second consideration will be the safeguards and physical security implications of plutonium fuel utilisation. The International Safeguards arrangements set up under the auspices of the International Atomic Energy Agency (along with the Euratom safeguards arrangements within Europe) provide assurances through containment, surveillance, seals, inspection and accountancy procedures that no fissile materials are diverted from the civil nuclear fuel cycle in a clandestine manner.

The use of plutonium fuels will require extra security precautions, due to perceived proliferation concerns. This would add to costs and institutional complexity.

These aspects are not central to this study, except insofar as they affect costs, but they are of considerable importance to governments and utilities making decisions on their fuel cycle strategy.

2.9.5 Safety

There are differences between MOX fuel cycles and conventional uranium cycles in terms of safety, mainly at the front-end of the cycle. As indicated earlier these require additional precautions during fuel fabrication and fresh fuel transit and storage compared with uranium fuel, but experience has already been gained with highly radioactive spent fuel.

Licensing authorities will need to be convinced that the use of MOX fuel in thermal reactors will conform to the safety standards laid down in national regulations, requiring them to be at least as safe as uranium fuelled thermal reactors.

The introduction of mixed oxide fuel into reactors designed specifically for uranium fuels may introduce operational constraints (see Annex B) and the extra costs of these will have to be taken into account. In this study attention has focussed on equilibrium replacement fuel batches where the costs are assumed to be minimal as a consequence of using only a limited fraction of MOX in each fuel batch.

PART 3

THE CURRENT STATUS OF MOX FUEL

3.1 Overview

Research on MOX fuels has been in progress in many OECD countries since the 1950s. Studies have concentrated on chemical and physical processes for fuel manufacture and fabrication, on the behaviour of the fuel on irradiation (fission gas release, dimensional changes, reactivity, etc.) and on its subsequent solubility and reprocessing (see for example refs. 34-39). As previously indicated studies have also examined the way in which its use affects reactor fuel management, reactor control and safety.

MOX fuel fabrication plants have been constructed and operated successfully in Belgium (Belgonucléaire), France (COGEMA), Federal Republic of Germany (Alkem), Japan (PNC), United Kingdom (BNFL) and the United States (Westinghouse Hanford Co., Kerr Mc Gee, Numec and United Nuclear). Current and planned fabrication capacities are listed in Table 19.

Table 19

PLANNED LWR MOX FUEL FABRICATION PLANT CAPACITIES

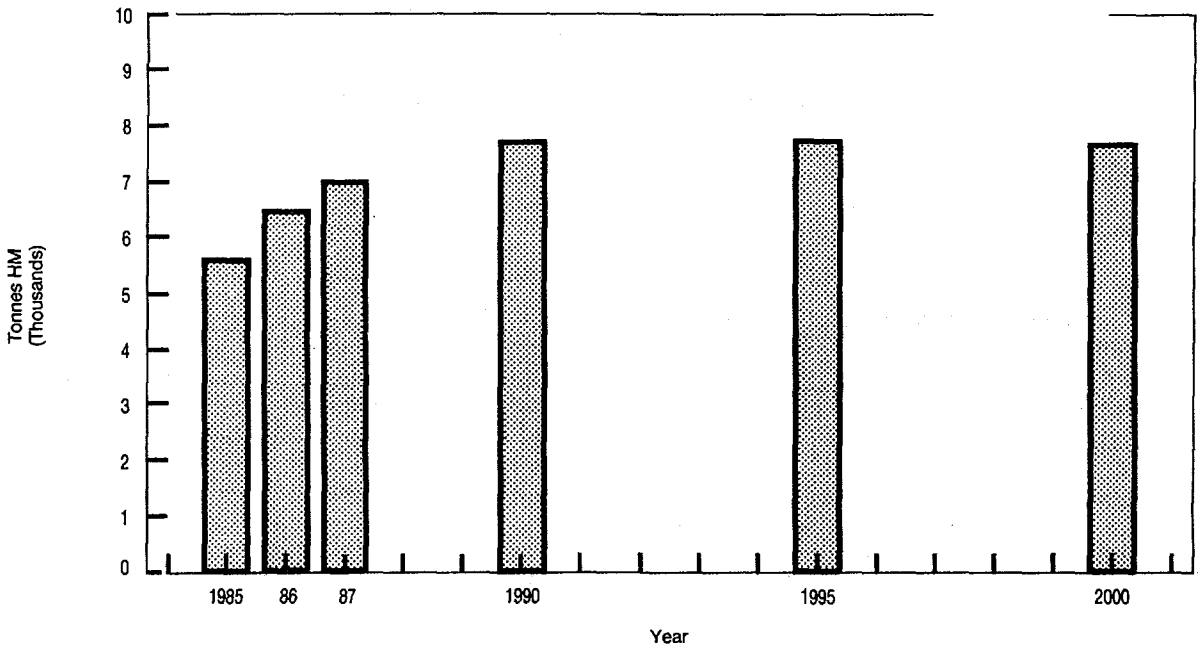
Basis: 90 % rated capacity expressed as tonnes of heavy metal

	1987	1990	1995	2000
FRANCE:				
CEA CFCa Cadarache	-	15	15	-
COGEMA MELOX*, Marcoule	-	-	100	100
BELGIUM:				
Belgonucléaire Dessel	15	35	70	70
FRG:				
Alkem Hanau	27	40	100	120
JAPAN:				
PNC Tokai**	9	9	35	35
UK:				
BNFL	-	-	-	50

* These plants are operated under the umbrella of Commox, a joint Cogema-Belgonucléaire company.

** Including MOX fuel for Advanced Thermal Reactors (ATRs).

Figure 24. **PROJECTED ANNUAL SPENT FUEL**
In OECD countries to 2000



* *Source:* Electricity, Nuclear Power and Fuel Cycle in OECD Countries, Main Data, OECD (NEA), Paris, 1988.

Table 20

REPROCESSING PLANT DESIGN CAPACITY
(Tonnes HM per year)

	Fuel Type	1986 (actual)	1987 (actual)	1990	1995	2000
France	LWR	400	400	700	1 750	1 750
	GCR*	500	500	500	500	500
Germany, F.R.	LWR	35	35	35	35	350
Japan	LWR	210	210	210	1 010	1 010
United Kingdom	Oxide	0	0	0	1 200	1 200
	Magnox	1 500	1 500	1 500	1 500	1 500
OECD TOTAL		2 645	2 645	2 945	5 995	6 310

* Data provided specifically for this report.

Source: Electricity, Nuclear Power and Fuel Cycle in OECD Countries, 1988, Table 9.

The first partial reactor load of MOX fuel was loaded into the Plutonium Recycle Test Reactor (PRTR) at Hanford in the US in 1960. The burn-up achieved was 18.5 GWd per tonne.

The first MOX PWR fuel was loaded into the Belgian BR3 pressurised water reactor in 1963, a reactor which continued to serve as a test bed for MOX fuel and which at its last refuelling contained 70 per cent of MOX assemblies. Since 1963 considerable progress has been made in demonstrating the satisfactory properties of MOX fuel. The FRG, for example, has manufactured and loaded over 38 000 MOX thermal reactor fuel rods and achieved burn-ups of up to 46 000 MWd per tonne (42). Some 32 000 MOX fuel rods (430 assemblies) have been manufactured in Belgium and irradiated in LWRs achieving burn-ups of up to 80 GWd per tonne (37). Large numbers of fast reactor Pu fuel rods and assemblies have been made in Belgium, FRG, France, the UK and the US and burn-ups in excess of 170 GWd per tonne have been achieved without difficulty.

The manufacture and use of MOX fuel can be regarded as an established technology and the use of 30 per cent MOX is now a commercial reality in France although the scale of operation still remains relatively small.

3.2 National Plans

The plans of OECD member countries differ significantly depending on their circumstances. Annex F contains summaries of individual national positions. Some like the USA and Canada have no current plans to reprocess spent civil fuel or to use recovered plutonium in commercial reactors, although the former country has an active fast reactor development programme. Others like Belgium, France, FRG, Japan and Switzerland do plan to undertake significant programmes of MOX recycle in thermal reactors. These latter countries have been committed to reprocessing for environmental reasons or in order to have plutonium for fast reactors.

The United Kingdom is another reprocessing country but it has up until now built gas-cooled reactors where the economics of plutonium recycle are less favourable than those for PWRs. The UK has sizeable and growing stocks of separated plutonium and is expected to have MOX fuel fabrication facilities in the 1990s.

The estimated thermal MOX fabrication capability summarised in Table 19 is small compared with the OECD production of 12 000 tonnes of uranium fuel p.a. in 2000 (5). It will utilise only a small fraction of the plutonium that will have been produced in thermal reactor fuel in the OECD countries, which will amount to well over 1 000 tonnes by 2000 (5). The quantities of spent fuel, the quantities of plutonium in spent fuel and the likely quantities of separated plutonium available for use before 2000 are summarised in Figures 24, 25 and 26. It will be seen that only a small fraction of the total plutonium produced in thermal reactor fuel will have been recovered by reprocessing by 2000 (Figure 26) and that only a relatively small part of that is likely to have been recycled in thermal reactors by the turn of the century (Table 19). The planned *oxide* fuel reprocessing capacity remains well below annual spent fuel arisings until beyond the year 2000 (Figure 24 and Table 20). The figures for plutonium in and recovered from fuel for Figures 25 and 26 have been calculated in round terms on the basis of conversion factors taken from ref. 1 and maximum recovery based on reprocessing plant capacity fully utilised for PWR fuel. The actual quantities of plutonium recovered could be substantially less than this but Figure 26 serves to illustrate the potential magnitude of the stocks and the use that could be made of them.

Figure 25. **PLUTONIUM (TOTAL) CONTAINED IN ANNUAL SPENT FUEL ARISINGS**
In OECD countries to 2000

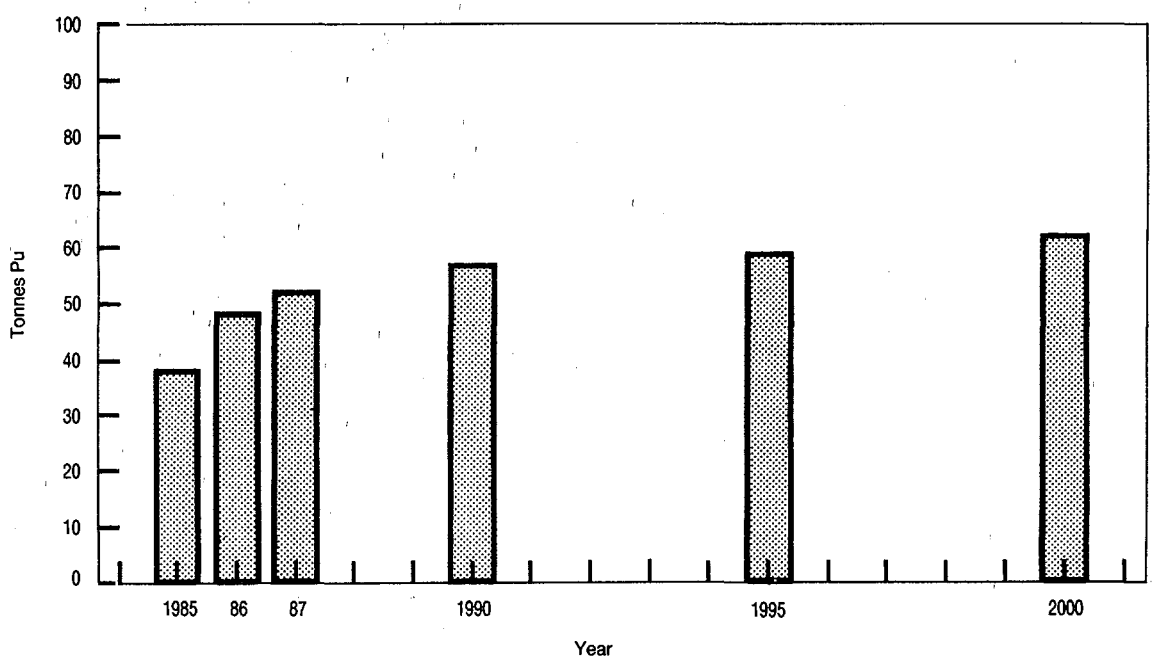
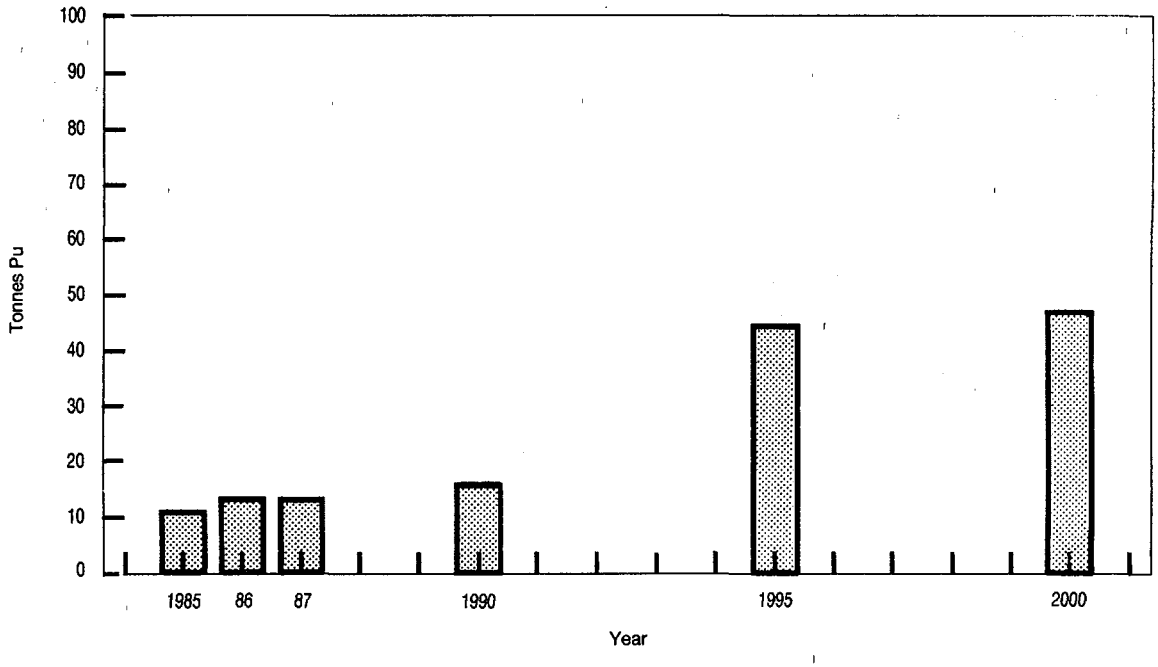


Figure 26. **ANNUAL PLUTONIUM RECOVERY CAPACITY***
In OECD countries to 2000



* Based on UO_2 for LWRs and 100 % availability of plant capacity. Actual plutonium recovery could be considerably less.

3.3 A Plutonium Market

Small quantities of plutonium have been sold from time to time for use in civil reactor fuel development and demonstration. Such sales take place under international safeguards.

As MOX fuel production and use expands it is possible that a market for plutonium or MOX might develop if there are countries with a surplus of separated plutonium that could be used by other countries to save fuel costs.

However if MOX fuel is used in a once-through mode without further reprocessing most larger countries with light water reactors will have the capacity to use their own plutonium and this will be more profitable for them than selling it for others to benefit from its use.

For this reason it seems unlikely that a significant international plutonium market will develop in the medium term, unless countries with plutonium stockpiles or a commitment to reprocessing plan to reduce their own nuclear generation capacity.

PART 4

SUMMARY, DISCUSSION AND CONCLUSIONS

This report has sought to explain the facts about plutonium and its potential use as a civil nuclear fuel. Attention has been centred on technical and economic issues. The participants note that there are important non-proliferation considerations with respect to reprocessing and plutonium utilisation that, while not discussed, must be addressed in each Government's decisions in this area.

Plutonium is a radiotoxic material but like other hazardous materials it can be handled safely. Extensive experience of its use and that of much more highly radioactive (and radiotoxic) materials has accumulated over the years. This gives confidence that there need be no technical or safety barriers to its use as a fuel in thermal or fast reactors, subject to the standard procedures of nuclear safety and licensing being applied. These are similar for all fissile materials and plutonium presents no unique problems although greater precautions are needed than with low enriched uranium for example.

Quantities of plutonium recovered from spent nuclear fuel from thermal reactors have risen and they will rise further as reprocessing continues, with global totals reaching 100s of tonnes by the year 2000, although this is only a small part of the total amount of plutonium that will by then exist in spent uranium fuels. Plutonium is a potentially valuable asset that depreciates slightly in value due to radioactive decay. Additionally storage of plutonium imposes costs on the owner and there is therefore an incentive to use it in thermal reactors now that it is evident that fast reactors will not be deployed commercially on any scale before well into the next century. This use would not preclude its subsequent use in fast reactors, although it could slow down the rate of their introduction if this were constrained by separated plutonium availability. At the present time this is not seen as a major concern and recycled plutonium fuel will remain an effective fuel for fast reactors.

For the purposes of this study attention has been focussed mainly on the economics of using separated plutonium (and the plutonium in spent fuel) in existing light water reactors in the 1990s.

The plutonium that has already been separated and for which the recovery costs have been paid (or which will be separated for contractual or policy reasons) does offer significant cost savings of 30 per cent or more when used in MOX fuel for equilibrium reloads of PWRs compared with uranium oxide fuels using uranium at around $80 per kg. It would be worthwhile economically at uranium prices down to around $50 per kg U using the reference values for enrichment and fabrication costs. However, on the basis of illustrative cost calculations, the overall savings as a percentage of fuel cycle costs for a given generating system are not large in relation to front-end costs, which account for a major proportion of the total levelised fuel cost for PWRs operating on a reprocessing cycle.

The situation where plutonium has not been separated and there is no existing commitment to its separation is both more complex and subject to greater uncertainty. There is no clear international consensus on the future costs of some stages of the nuclear fuel cycle, particularly the back-end, and for some of them there is no established commercial service in prospect. Each country may have to provide its own facilities for spent fuel storage and spent fuel or reprocessing waste conditioning and disposal. These, like reprocessing plants, will have costs that are scale dependent. For this reason judgements on the costs of the different back-end options will differ from country to country.

Whilst uncertainties in these costs do not affect greatly the overall costs of the nuclear fuel cycle, they are significant in relation to the differential costs between the use of MOX and uranium oxide fuels in the case where the former meets the net costs of plutonium recovery from spent fuel.

It has been shown here that in such a case MOX use (and reprocessing) becomes economically attractive when the uranium-235 substitution value of plutonium and uranium recovered from 1 kg of spent fuel exceeds the difference between the present worth costs of reprocessing (including waste conditioning and disposal) and spent fuel storage, conditioning and disposal, both per kg HM (with a small discounting adjustment related to the interval between reprocessing UO_2 fuel and the use of recovered plutonium in MOX fuel fed to a reactor). It has also been shown that the sum of the substitution values based on use in 33 000 MWd per tonne fuels can vary considerably when they are derived using plausible values of uranium, enrichment and UO_2 and MOX fabrication costs.

The sum of the substitution values derived from the illustrative range ($129 per kg HM to $245 per kg HM) would be widened further if MOX were recycled by coprocessing with uranium fuels (higher differential), higher burn-up fuels were being used (higher); or if spent fuel reprocessing (slightly lower) or plutonium use after recovery (lower) were deferred significantly.

A high differential is more economically favourable to MOX use and arises with higher uranium and enrichment costs and lower MOX fabrication costs. A low differential is less favourable to reprocessing and MOX use.

Unfortunately it was beyond the remit of this working group to develop new detailed costings of the back-end of the uranium fuel cycles, and the values presented in the previous study (4) were not considered to be adequate for purposes of detailed comparisons with the fresh data. This reinforces the need for the forthcoming studies on spent fuel and reprocessing waste storage and repository costs by another NEA working group.

With the wide range of potential front-end costs and the considerable uncertainty surrounding back-end costs it is not surprising that views on the economic attractions of reprocessing specifically to recover plutonium for recycle in thermal reactors can vary considerably from country to country.

Higher burn-ups enhance the saving advantages of MOX fuel made from free plutonium over similarly higher burn-up uranium fuels but, even if lower burn-up MOX fuels are compared with higher burn-up uranium fuels on an energy output basis, MOX appears to have an advantage using the illustrative costs. In practice the burn-ups of uranium and MOX fuels in a reactor will be only slightly different. There will be a tendency to manage the individual reactors of a coherent reactor park in a similar way, irrespective of whether they are MOX-fuelled or not.

The thermal recycle of separated plutonium converts it once more into spent fuel. If it is a country's policy to reprocess spent fuel, the MOX fuel replaces an equivalent quantity of uranium fuel and the reprocessing costs of both are similar. The use of the separated "free" plutonium in the short term to fuel thermal reactors will not mean that early fast reactors have to pay for the recovery of plutonium for their initial fuel inventory if thermal MOX is reprocessed as a matter of course as in case A. In case B, however, fast reactors would be faced with paying net costs of plutonium recovery. This could, in some countries, affect perceptions of fast breeder start-up costs adversely. However, fast reactors are self-sustaining and only need fresh plutonium for their initial launch so that their equilibrium or total levelised fuel costs, which are dependent mainly on fast reactor fuel recycling, will not be greatly affected.

Attention has been drawn to the wider strategic, institutional and safety considerations that may influence decisions concerning the future use of MOX fuel in thermal reactors and the technical and economic factors that will influence the specific fuel choices. In some cases these will be the factors that dominate choices since, as was pointed out before (4), the differences in the costs of alternative thermal reactor fuel cycles are not large when compared with the overall costs of generating electricity.

The current position and plans for MOX use indicate that this will grow within OECD member countries, notably in certain European countries and Japan, although it will remain small in relation to the total use of nuclear fuel. Countries like the United States, Canada and the United Kingdom have no current plans to use MOX fuel in thermal reactors, although the UK and the US use Pu fuels in fast reactors. (The UK lacks economic incentive to use MOX in AGRs).

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Annex A

SPENT FUEL STORAGE

The early gas-cooled, graphite moderated reactors which were commissioned in France and in the UK during the 1960s used fuel clad in a magnesium alloy. This type of cladding is subject to quite rapid aqueous corrosion and this places a limitation on the length of time such fuel can be stored underwater. In the early stage of commercial nuclear power development when these reactors were designed, it was thought that in the longer term future uranium would be in short supply; a rapid progression to the use of fast reactors was envisaged and prompt reprocessing was seen as a necessity. Under these circumstances, the short-term use of underwater storage was seen as acceptable and all stations, with the exception of the last to be commissioned in 1970 at Wylfa in the UK, were equipped with cooling ponds. At Wylfa, the fuel is stored in specially designed air-cooled dry stores and this provides greater flexibility in the management of spent fuel.

Noting that the early gas-cooled reactor stations will be phased-out through the 1990s, at this late stage in the programme a change to dry storage would be an unwarranted expense. For this reason, the spent fuel from the early gas-graphite reactors has to continue to be reprocessed to a prompt timescale. This gives rise to a steadily increasing stock of plutonium.

Annex B

MOX USE AND THERMAL REACTOR SAFETY*

One review of the safety aspects of MOX use in light water reactors was undertaken by the EEC. They employed eight contractors who undertook calculations on the basis of a reference equilibrium uranium fuel cycle and at least two plutonium recycling schemes: the first with a total core loading of about 30 per cent of plutonium assemblies and the second with either 70 per cent or 100 per cent of plutonium assemblies.

The aim of the theoretical studies was to get some insight into the spectrum of questions from the physics point of view, that may arise in the case of LWR Pu-recycling:

- Will the steady state and accident behaviour of a MOX-fuel core be very different from the U-core?

- Will there be important differences between U- and MOX-fuel, as far as core behaviour is concerned?

- Will there be any plant modifications needed in the case of MOX-fuel assembly insertion?

- What will be the maximum amount of MOX-fuel assemblies that can be loaded into the core, without causing severe restrictions or necessary modifications?

- Will the licensing procedures, with respect to the physical core parameters, be affected by core loading?

The general conclusions from the work is that with MOX recycling in the range of self-generated recycling (20-30 per cent of core loaded with MOX-fuel) no major problem will arise with respect to the above mentioned points. Moreover, some studies pointed out that, even at higher plutonium loadings, no severe restrictions are to be expected.

More specifically, the study concludes that:

- The recycling of about 30 per cent of mixed oxide fuel in large LWR cores should not induce special problems, provided precautions are taken in core design to minimise the differences with UO_2 cores, taking into account a limited margin of uncertainty.

- The influence on core behaviour during the hypothetical accidents investigated in the studies was not very important and does not necessitate restrictions for at least a 30 per cent Pu fraction in the core. Obviously, the possible case of non-optimised loading patterns and the uncertainty about some parameters and event sequences should not be forgotten.

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* Edited extracts from "Analysis and Synthesis of the theoretical studies performed on the control and safety of LWR's burning plutonium fuel", EUR 8118BN.

- From the steady state and safety points-of-view, the maximum allowable quantity of plutonium in a core depends on many specific factors. In principle, a 100 per cent MOX-core could be operated under certain conditions of loading pattern and shutdown margins, but more extended studies need to be performed to prove the feasibility for each design.

- Storage pool design with respect to criticality will not be affected by the use of MOX fuel assemblies.

- Pool shielding requirements will be the same for UO_2 and MOX fuel.

- Decay heat and the neutron level without shielding will be slightly higher for pools loaded with MOX.

Annex C

THE REFERENCE PWR

Description of the PWR parameters utilised for the fissile material balance calculation.

1. Preliminary remark

Although an EDF plant was taken as input data, the calculated refuelling schemes (including discharge burnups, reload batches, cycle length, etc.) are not deemed to represent the EDF perspectives in this respect.

2. General information

Reactor type	PWR
Power output : gross/net (MWe)	921/880
(MWt)	2785
Efficiency gross/net (%)	33.1/31.6
Coolant temperature inlet/outlet (°C)	286/323
pressure (kg/cm2)	158

3. Reactor core

Active core h x d (m)	3.66 x 3.04
Fuel inventory (t U+M)	72.5
Fuel assemblies	157
Rods per assembly	264 in a 17 x 17 geometry
Specific power (kW/kg U+M)	36.6
Core power density (kW/l)	99.9
Linear power density (kW/m)	17.8
Cladding material	Zry 4
Cladding thickness (mm)	0.57

Operating + shutdown periods (calendar months) 12 (i.e. annual cycle)

Reloading schemes	1/3 core	1/4 core	1/5 core
Discharge burnup (GWd/t U+M)	33	43	53
Fresh fuel loaded per year (ass)	52	40	32
(t U+M)	24.0	18.5	14.8
In the MOX option, fresh MOX loaded per year (ass)	16	12	10
(t M)	7.38	5.54	4.01
Energy production (EFPD : equivalent full power days/year)	284	286	282

Annex D

MULTIPLE PLUTONIUM RECYCLING IN PRESSURISED WATER REACTORS

Recycling of reprocessing plutonium in pressurised water reactors is now a reality: in 1987 for the first time 16 MOX assemblies were loaded in the Saint Laurent B-1 reactor for a 33 GWd per tonne cycle.

The next step will be to check whether it will be possible in the medium term to multiply recycle plutonium. France considers that multiple plutonium recycling in pressurised water reactors is feasible and should not raise any serious difficulty for the next few decades, as shown by the following analysis of technical data and EDF programmes.

1. Technical Analysis

During a PWR cycle, the fissile plutonium isotopic content diminishes to an asymptotic value as further recyclings occur. For instance, Figure 1 of this Appendix shows the variation in fissile plutonium content with the number of recyclings (Pu curve: recycling without mixing). For plutonium from the 33 GWd per tonne cycle of present PWRs (PWR 33 on Figure 1 of this Appendix), the fissile plutonium content is 70 per cent. After the first recycling, it falls to approximately 60 per cent, and after a second recycling to 53 per cent. For plutonium from the 45 GWd per tonne cycle, the levels will be markedly lower.

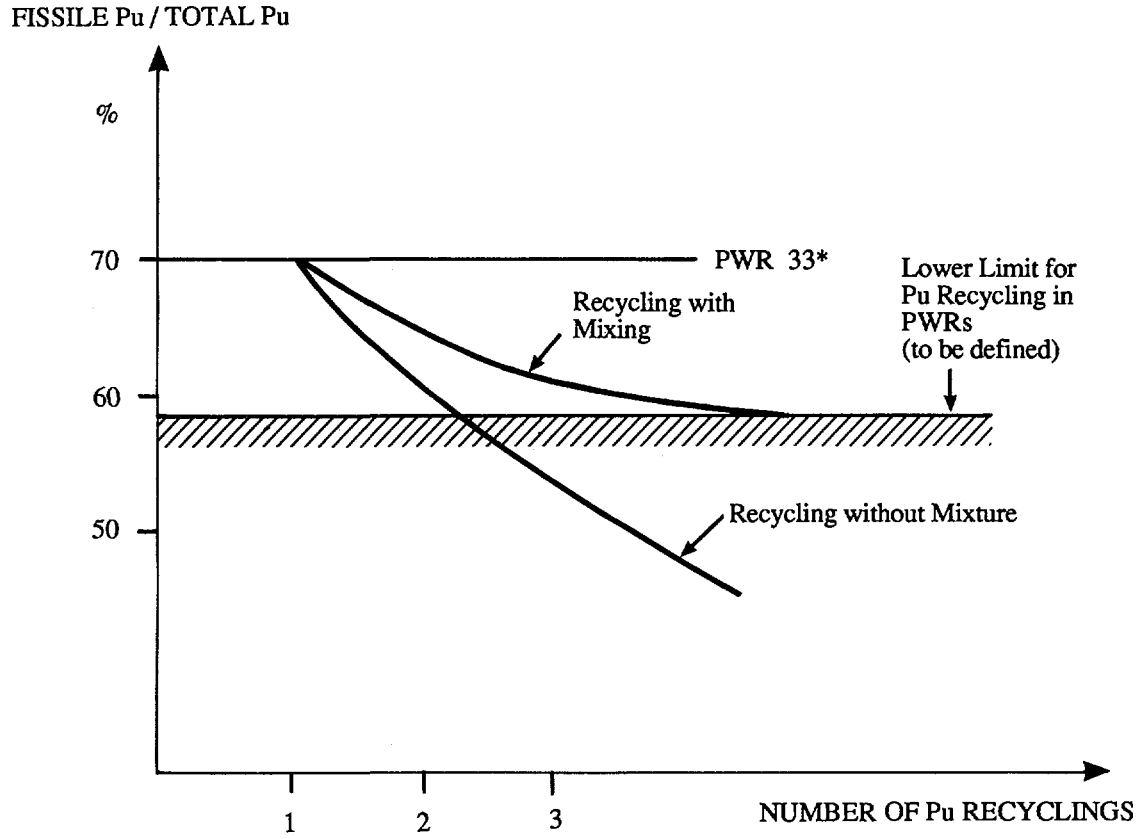
It is therefore obvious that multiple recycling of plutonium in PWRs would be limited more or less to two recyclings. Below a limit value (to be defined), the use of plutonium is incompatible with operating constraints and safety requirements for current pressurised water reactors owing to, among other things, the excessively high plutonium enrichment level.

In order to overcome this difficulty, the fissile plutonium content of plutonium can be increased by mixing, *in the initial reprocessing stages*, spent fuel of different origins (mixture of plutonium MOX fuel and standard enriched uranium PWR fuel).

The procedure for mixing during reprocessing is outlined on Figure 2 of this Appendix. Shearing of fuel elements and dissolving in nitric acid are performed in two separate trains operating simultaneously, one for UO_2 assemblies and the other for MOX assemblies. The solutions are then mixed before being transferred to the extraction unit.

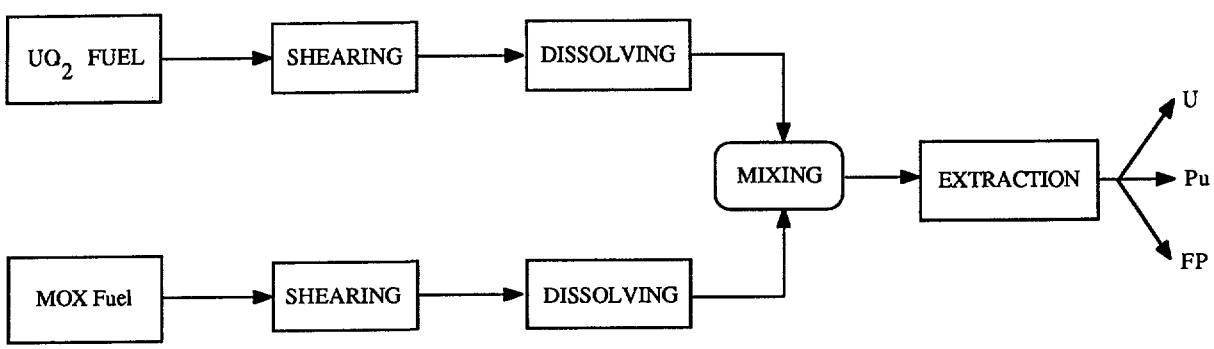
The proportions used in the mixture must be such that the plutonium available following reprocessing has a fissile plutonium content allowing at least three recyclings. The method is represented by the curve "recycling with mixture" on Figure 1.

Figure 1. **FISSILE PLUTONIUM LEVEL AGAINST THE NUMBER OF Pu RECYCLINGS WITH AND WITHOUT MIXING AT THE REPROCESSING STAGE (THEORETICAL DIAGRAM)**



* PWR 33 : Fissile Pu level obtained following irradiation of an enriched UO_2 fuel in a PWR cycle at 33 GWd / t

Figure 2. **PRINCIPLE OF MIXING DURING REPROCESSING**



According to currently available data, a mixture of approximately 1 MOX assembly treated in dilution plus 4 enriched uranium PWR assemblies would meet the target shown on the curve. More specifically, this mixture would lead to a content of approximately 64 per cent fissile plutonium at the beginning of the second recycling, and approximately 62 per cent at the beginning of the third recycling for a 33 GWd per tonne cycle. The corresponding levels would be about 63 and 59 per cent, respectively, for a cycle of 45 GWd per tonne. This dilution rate is compatible with the operation of the UP2-800 plant at La Hague.

2. Fuel Cycle Duration

As far as the fuel cycle is concerned, two successive plutonium recyclings would be separated by a period of ten years divided as follows:

- Length of stay inside the reactor of about three years;
- Cooling period, prior to reprocessing, of about five years;
- Reprocessing and fuel fabrication time of about two years.

Consequently, three successive plutonium recyclings would cover a period of 30 years.

3. EDF-MOX Programme

Under the current EDF programme, MOX fuel will be gradually introduced in French pressurised water reactors at the rate of 30 per cent MOX fuel assemblies per reloading.

Consequently, a steady rate of about 100 t per year of MOX fuel will be reached by 1995. Meanwhile, by the same year a flow of about 1 200 t per year of enriched uranium fuel will be achieved. MOX fuel will then account for less than 10 per cent of fuel to be reprocessed, which is more than compatible with the dilution level envisaged in section 1 (1 MOX to 4 enriched uranium assemblies).

In conclusion, all the above considerations indicate that during the *next 30 years* multiple plutonium recycling in PWRs is feasible.

In technical terms, three successive recyclings would be possible with the use of a MOX fuel-enriched uranium fuel mixture during reprocessing (1 MOX assembly to 4 enriched uranium assemblies).

The above analysis is based on current data, to be updated as and when experience is acquired in the operation of reactors using MOX fuel (probable increase in fuel performance). Moreover, it does not take into account future technological advances (e.g. use of advanced reactors), which in any case will lead to improved use of plutonium by the next century.

Annex E

ECONOMIC METHODOLOGY

Although this study has not looked at whole reactor life fuel costs there are leads and lags in the substitution reloads which necessitate adding costs incurred at different times.

As in earlier studies (1, 4) the discounted costs have been calculated. In this case the time of feeding fuel into the reactor was taken as the base date.

If individual stage costs C_1, C_2, etc. relate to uranium purchase, conversion, enrichment, etc. then the total "discounted" cost of one kg of fuel will be:

$$\sum C_i \, (1+r)^{-t_i}$$

where t_i yrs is the time *after* feeding fuel into the reactor that the charge is incurred.

In practice t_i is negative for most of the costs included in this study in which case the total fuel cost includes interest at r% p.a. compound on the expenditures on fuel prior to feeding to the reactor.

For a fuller description of the application of discounting to the nuclear fuel cycle see "The Economics of the Nuclear Fuel Cycle" (4).

Annex F

NATIONAL VIEWS ON PLUTONIUM USE - COUNTRY ANNEXES

BELGIUM

The Industry Status

The Belgonucléaire (BN) company was created in 1957. Its plutonium fuel fabrication plant is situated at Dessel near Mol, BN concentrating all Belgian activities on design and manufacture of mixed oxide fuel subassemblies for LWRs and for fast breeders. This facility came into operation in 1973. The basis was important experience gained progressively, first from R&D work after 1959 at the National Research Center CEN/SCK of Mol, and then from the results obtained in a Belgonucléaire pilot plant, operated from 1968 and 1973. The first MOX assembly to have been recycled in the world was fabricated by Belgonucléaire and loaded in BR3, a small PWR reactor, as early as 1963, 25 years ago. Since then this reactor has been used to test fuel rods from most fuel suppliers in the world, through numerous multilateral agreements for experimental irradiation programmes, accumulating a large experience in nuclear fuels. The last reload placed in BR3 contained 70 per cent of MOX fuel. Another milestone was the loading of the first complete MOX reload in a large reactor: Garigliano in Italy in 1975 based on 4 lead test assemblies incorporated in 1970. The company also fabricated 40 per cent of the first core of the German FBR, SNR-300. Today, the Dessel plant is equipped for a yearly production around 35 tonnes HM (i.e., 40 tonnes MOX). Extension is foreseen in an adjacent plant for the mid 90s.

COMMOX is a joint venture founded in 1984, between COGEMA (60 per cent) and Belgonucléaire (40 per cent) for commercialisation of MOX fuel. COMMOX has the responsibility for producing MOX fuel, pellets, and fuel rods, manufactured in plants at Dessel, Cadarache and Marcoule. It also provides associated services through both parent companies. Flexibility in MOX fuel usage, and suppression of Am-241 build-up problems, are achieved by immediate manufacturing of fuel rods or assemblies which can be stored up to the time the utility decides to use the MOX. COMMOX has the full back-up of the two mother companies.

Trends of Plutonium Use

Although Belgium has opted for nuclear fuel reprocessing, it is directing its effort towards a flexible policy consisting of reprocessing part of its spent fuel abroad, while the rest is stored temporarily for a period of time which will depend on the evolution of the price of uranium, reprocessing and enrichment services.

The principle of plutonium recycle in light water reactors is accepted separately from fast reactor needs, but the present reprocessing programmes do not imply commitment to a recycling programme before reprocessing of Belgian fuel in the new facility at La Hague.

Plutonium is managed by SYNATOM. The MOX fabrication and technology are the responsibility of Belgonucléaire.

Future Plans

- Capacity of the Belgonucléaire MOX fabrication plant: 35 tonnes HM per year.
- The plant can be extended on short notice with 1 or 2 additional modules of 35 tonnes HM per year, according to the development of the market (the multimodular plant is referred to as DEMOX - the Dessel MOX plant).

CANADA

Institutional Framework

In Canada, Atomic Energy of Canada Limited (AECL) has the lead role in developing the peaceful uses of nuclear energy, whereas the various provincial electric utilities, such as Ontario Hydro, Hydro-Québec and New Brunswick Power, build, own and operate the nuclear power plants. All of these organisations have undertaken significant activities in the spent fuel management area, both individually and collectively.

A Nuclear Fuel Waste Management R&D programme led by AECL is now well established with broad Canadian participation. The overall objective of this programme is to ensure that there will be no significant effects on the environment from these radioactive fuel wastes.

As the major producer of spent fuel, Ontario Hydro, is extensively involved in the research and development programme. Plants in Québec (Gentilly-2) and New Brunswick (Point Lepreau) have begun to produce small quantities of spent fuel, and Hydro Québec and New Brunswick Power are keeping abreast of the research and development programme.

Current Practice

Used fuel is currently stored in water-filled storage bays at the power reactor sites in Canada. This storage method can provide safe and reliable storage for many decades. Canadian utilities' current on-site storage capacity for used fuel allows time for developing an integrated disposal strategy and permits decisions on the ultimate fate of the fuel to be deferred.

A study performed in 1979 showed that, for Ontario Hydro, on-site storage is the most cost effective option for interim storage of used fuel. The on-site storage policy will be reviewed on a periodic basis as technical, socio-political and economic factors change.

Spent fuel is a potential energy source. A decision to utilise it will depend upon the future economics of fuel reprocessing and of advanced fuel cycles relative to the current once-through natural uranium cycle.

Future Plans for Used Fuel Management

CANDU reactors currently operate on a natural uranium, once-through fuel cycle, i.e., the fissile material in the used fuel is not currently being recycled. In order to keep the options open for final disposition of the fuel, technologies are being developed for the immobilisation of both used fuel and fuel recycle waste. The choice between fuel disposal and recycling is being deferred for some time. Concepts for the storage of fuel for extended periods (greater than 50 years) are being developed also.

In looking ahead to the period when alternatives to the once-through cycle are required, the option is available to develop thorium as a fuel for CANDU reactors. The cycle is predicated on the use of plutonium as the initial fuel material to be blended with the thorium. The ultimate goal is to be prepared to proceed towards a self-sufficient thorium-223/uranium cycle. The economics of this cycle, based on cost of fuel cycle operations as they are practiced today, make its implementation in Canada unattractive in the near term. The same can be said for recycling CANDU plutonium with natural uranium fuel (Pu-U_{nat} cycle) in CANDU reactors. Two attractive fuel cycles involve the use of recycled LWR fuel in CANDU reactors; one uses the recovered uranium and the other the recovered uranium and plutonium. The first of these cycles avoids the re-enrichment of the recovered uranium while the second offers a possibly simpler reprocessing step in which uranium is not separated from plutonium. Current efforts are aimed at possible implementation of slightly enriched uranium (SEU) utilisation in current and future CANDU reactors. The results from implementation and development of the SEU cycle will apply to other advanced cycles being considered for CANDU, thus providing confidence that they will be credible alternatives.

Factors Influencing Spent Fuel Management Policy

From a technical resource and economic viewpoint, the use of plutonium in CANDU does not appear attractive now. When these conditions change a shift in the programme emphasis may be proposed.

FEDERAL REPUBLIC OF GERMANY

Status of Industry

General policy and institutional framework

It is generally agreed that an optimal utilisation of plutonium is economically achievable only in fast breeder reactors, but the time-scale for the commercial operation of these reactors has turned out to be longer than expected. Additionally, plutonium demand that has to be met by the German partners in the European breeder programmes is exceeded by the quantities of the material arising under the reprocessing contracts which the German utilities have concluded with COGEMA in France and BNFL in England to secure the back-end of the fuel cycle of their nuclear power plants, and by the quantities becoming available in the Karlsruhe reprocessing plant (WAK).

In the Federal Republic of Germany, plutonium accumulation will have increased to about 15 tonnes of fissile plutonium (Pu_f) by 1995. This estimate is based on the reprocessing programmes of COGEMA, BNFL and WAK in accordance with existing contracts. There is limited demand - about 490 kg Pu_f a year - from breeder programmes. This is made up of 140 kg which have to be provided by the German partners for the refueling of Superphenix and 350 kg for SNR 300 whose commissioning has not yet been decided. In addition, the German utilities are to build the Wackersdorf reprocessing plant, which will separate about 2000 kg Pu_f a year from irradiated fuel, starting in the mid 1990s.

Because political considerations lead to reservations about the storage of larger quantities of plutonium, the German utilities have committed themselves to immediate recycling in thermal reactors of all the plutonium which arises in excess of breeder demand.

In 1981 the utilities concluded a co-operation contract with the plutonium fuel fabricator ALKEM. The contract was intended to secure sufficient capacity for the fabrication of MOX fuel assemblies, to provide adequate opportunity for their insertion in light water reactors, and to demonstrate plutonium recycling on an industrial scale. A prerequisite was ALKEM's extensive experience, dating from the 1960s, in the field of MOX fuel rod fabrication. The contract, which ran until 1988, included also that all plutonium which could not be used immediately in fast breeder reactors should be pooled and utilised for thermal recycling. For economic reasons it was decided to concentrate primarily on recycling in PWRs. The respective licensing procedures have been or are being carried out for the greater part of the power plants already in operation in the FRG. The programme is scheduled to be extended to include also BWRs in order to increase the recycling capacity.

Early demonstration

An early demonstration programme for plutonium recycling in thermal reactors was largely financed by the Bundesministerium für Wissenschaftliche Forschung (now the Federal Ministry for Research and Technology). It began in 1966 with the insertion of an all-MOX fuel assembly in the Kahl boiling water reactor. Later, several reloads of different designs (all-rod and island) were tested in this reactor.

Early in the 1970s the pre-commercial phase was initiated with a comprehensive programme to demonstrate plutonium recycling. This covered self-generated plutonium in the KRB boiling water reactor and in the KWO pressurised water reactor. The programme was highly successful with respect to the behaviour of the fuel assemblies during reactor operation. Average burn-ups were comparable with those of the uranium fuel assemblies inserted at the same time.

It was thus demonstrated that it was possible to design and fabricate MOX fuel assemblies that were fully compatible with uranium fuel assemblies and the reactor system. All the fuel assemblies of the demonstration programme have been discharged in the meantime.

If MOX fuel assemblies were to be reprocessed without difficulty by the Purex process, the plutonium they contained had to be completely soluble in nitric acid before insertion in the reactor. This was found not to be so; reprocessing was feasible only after considerable extra expenditure. The demonstration was suspended and improved fabrication processes were developed.

Fabrication processes

There are at ALKEM two main fabrication processes for MOX fuel: the AUPuC and the OCOM process. The Ammonium-Uranyl-Plutonyl-Carbonate (AUPuC) process was developed on the basis of the Ammonium-Uranyl-Carbonate (AUC) process used for UO_2 conversion. Feed materials are plutonium and uranium nitrate solutions arising during reprocessing. Economic and technical considerations made it advantageous to apply the so-called master-mix concept. In this case the plutonium content of the $(U/Pu)O_2$ powders coming from co-conversion is as high as possible - at the upper boundary of the complete solubility of mixed crystals (40 per cent) - and is brought to the desired plutonium concentration by mixing with UO_2 powder. The AUPuC process allows the separation of americium and provides an oxide powder with favourable physical properties. The solubility of plutonium in unirradiated fuel is higher than 99 per cent.

Over 90 per cent of the plutonium supply currently comes from COGEMA's La Hague reprocessing plant in the form of PuO_2 powder. Therefore, ALKEM developed for this material the Optimised Co-Milling (OCOM) process. For economic reasons, a mixture containing up to 30 per cent plutonium is milled in this process. The master-mix is blended in an additional step with free-flowing UO_2 powder to the specified low plutonium contents needed for thermal recycling. After pressing, sintering and grinding the MOX pellets exhibit a solubility of >99 per cent, as specified.

Both new processes were sufficiently developed by 1980 to continue the early plutonium recycling demonstration programme with MOX fuel using the AUPuC and the OCOM process.

Design

In the FRG, the MOX fuel assemblies of which the fuel rods were fabricated by ALKEM are designed by KWU.

To meet the requirements of compatibility of recycling fuel assemblies with the other fuel assemblies in the core, such fuel rods and assemblies are subject to the same thermohydraulic, thermal and mechanical design limits as uranium fuel assemblies. The mechanical design of MOX fuel assemblies is identical to the mechanical design of uranium fuel assemblies with the exception of the fissile material. In particular the same geometry and structural materials are used.

In the case of MOX fuel assembly design large thermal capture and fission cross sections of the plutonium isotopes and important resonances have to be considered in comparison to uranium fuel. Further for economic fabrication, transport and storage reasons especially in the case of MOX, it is useful to concentrate the fuel in fuel assemblies of the all MOX type instead of the island type fuel assemblies.

In any case of MOX insertion, e.g., in an amount equivalent to self generated recycling or higher, reactivity coefficients, kinetic behaviour, hot channel factors, and the worth of the shutdown systems must meet the design criteria and fulfill the requirements for safe reactor operation.

Experience

Under the co-operation agreement between the nuclear utilities and ALKEM, fabrication of thermal MOX fuel began in 1981. In the same year the first fuel manufactured by the new processes was inserted in the Obrigheim nuclear power plant. Since then, MOX fuel assemblies have been fabricated for the Neckarwestheim, Unterweser, Grafenrheinfeld, Brokdorf and Grohnde plants in Germany, and for the Beznau-2 plant in Switzerland. Fuel rod fabrication capacity at the ALKEM plant is now app. 25-30 tonnes HM of MOX fuel a year and is planned to increase up to app. 40-50 tonnes HM in 1988 and later.

The fabrication experience gained in the FRG since 1966 until end 1988 can be summarised as follows: for LWR MOX fuel 399 fuel assemblies containing 54 500 fuel rods with 102 400 kg HM or 2900 kg Pu_f; for FBR MOX fuel 205 fuel assemblies containing 26 000 fuel rods with 5900 kg HM or 1400 kg Pu_f.

Future Plans and Factors Influencing Policy

The German plutonium programme is based on the quantities of plutonium which are expected to come from the reprocessing of spent fuel according to existing reprocessing contracts of German utilities with COGEMA, BNFL, the existing reprocessing plant of WAK in Karlsruhe and the later German reprocessing plant WA 350. The expected quantity can be estimated as about 30 tonnes of Pu_f up to the year 2000.

Initially for cost reasons, standardised MOX fuel assemblies were made for PWRs. Increased throughput has brought large reductions in fabrication costs. Today, depending on actual costs for enriched uranium, costs of MOX fuel assemblies are comparable with those of enriched uranium fuel assemblies. Because breeders have relatively low requirements, the whole of the quantity of plutonium arising from reprocessing cannot be recycled in PWRs alone. In future it will also be recycled in BWRs. It is planned for the future to increase the number of power plants recycling plutonium, for example up to 8 PWRs and 3 BWRs. Therefore, ALKEM is currently planning to increase its fabrication capacity to 120 tonnes HM of MOX fuel/year which is scheduled to come into operation in 1992.

The recycling of plutonium described shows that closing the fuel cycle by reprocessing and thermal recycle is feasible on an industrial scale and that the same levels of reliability and safety required by the nuclear standards in the FRG are achieved in reactor operation. That recycling of fissile materials is a technically and economically viable solution in closing the fuel cycle is demonstrated by the extended recycling experience in the Federal Republic of Germany.

FINLAND

The utilities are responsible for the management of spent fuel including its final disposal or the disposal of reprocessing wastes. As a matter of national policy they are instructed to seek possibilities for the disposition of their spent fuel abroad. The spent fuel from Loviisa reactors is sent back to the Soviet Union. For the spent fuel from Olkiluoto reactors the utility has to prepare for final disposal in Finland. The current R&D work is based on direct disposal of spent fuel after long-time interim storage (the storage facility is operating since 1987). Reprocessing remains as an option; however this alternative is currently considered to lack economic incentive.

FRANCE

The Industry Status

The accumulated experience

Plutonium:

The COGEMA involvement in plutonium related activities includes the reprocessing of irradiated LWR fuel assemblies, the handling, storage and transport of plutonium, and the reprocessing of mixed uranium/plutonium oxide assemblies.

Since 1962, CEA has operated the plutonium fuel fabrication facility of Cadarache, which has supplied fuel for the fast breeder reactors RAPSODIE and PHENIX. This facility has also manufactured the first core of SPX 1, the 1200 MWe FBR of Creys-Malville, and is currently involved in the fabrication of the reloads. To date, CFCa has manufactured 135 tonnes of oxide containing 24 tonnes of plutonium.

Reprocessed uranium:

Conversion of uranyl nitrate to UF_6 containing reprocessed uranium (RepU) started at COMURHEX ten years ago. The COMURHEX Pierrelatte plant (350 tonnes per year) has converted around 1 600 tonnes of RepU since then, with nitrate coming from COGEMA-La Hague, as well as from the DWK and WAK facilities in West Germany. At COGEMA Pierrelatte, a new facility with a capacity of 600 tonnes per year, is carrying out the conversion of uranyl nitrate to oxide.

Research and Development

CEA and Fragema are working on the design and improvement of MOX fuels for high burn-ups, and also for advanced reactors. But the most exciting programme in the R&D field for recycling materials is the laser enrichment (AVLIS) programme of CEA/COGEMA, which has the objective of entering commercial service by the late 1990s, firstly devoted to RepU. The characteristics of the AVLIS process are such that a very high selectivity for uranium-232 and the other undesirable minor uranium isotopes may be expected. In that case, over-enrichment in uranium-235 will not be needed to compensate for the neutron absorber uranium-236. Moreover, selective separation of uranium-232 would ease the fuel fabrication constraints.

Services to customers

The COMMOX Franco-Belgian joint venture between COGEMA and Belgonucléaire has been described under Belgium.

For RepU services, COMURHEX and COGEMA are associated in UREP, a 50/50 joint venture. Their marketing forces jointly offer complete services from nitrate collection at the reprocessing plant, transportation to Pierrelatte, transfer and conversion to the form desired by the customer, conversion to UF_6 or into oxides. For customers requiring storage for several years, U_3O_8 provides a stable chemical form. Suitable UO_2 is also available for utilisation in MOX manufacture.

Institutional Framework

In France the main choices relating to nuclear energy, reactors and fuel cycle plants are made on the basis of joint discussions between Public Authorities, the CEA and EDF. Technological options are usually selected by the CEA and EDF and feasibility demonstrations for those chosen are carried out jointly or independently by the two organisations. Industry is then requested to make cost estimates for the processes and to construct the necessary industrial installations.

Fuel cycle industrial and commercial activities are conducted by several private firms, the main one being COGEMA, a wholly owned subsidiary of the CEA-Industrie group.

Future Plans

Beyond the CEA/Cadarache plutonium fuel fabrication plant capacity, COGEMA is going to start construction at Marcoule of a large MOX fabrication facility called MELOX, whose capacity, 100 to 120 tonnes per year, is to come on line from 1993. Such a large plant could lead to important cost reductions in MOX fuel fabrication.

For the conversion of reprocessed uranium to UF_6 for re-enrichment, COMURHEX and COGEMA are planning large capacities corresponding to the La Hague nominal reprocessed uranium output or more. Its full scale realisation would lead to cost reductions.

Re-enrichment of RepU in the Eurodif plant at Tricastin requires a special operation programme to avoid mixing of undesirable uranium isotopes U-232, U-234, U-236 with fresh product. Eurodif has studied and experimented with the possibility of batch re-enrichment of RepU, in order to isolate, through dedicated campaigns, the irradiated material from the fresh.

Some factors which have contributed to the decisions

1. Economic comparisons between open and closed cycles have shown that there is little difference between the two although the once-through solution shows a slight advantage with a fairly low uranium price.

For example, the study conducted by NEA in 1985 on the economics of the nuclear fuel cycle showed that reprocessing and once-through fuel cycle costs overlap. Depending on the assumptions selected, costs range from 6.6 to 10.9 mills/kWh for reprocessing and 5.9 to 10 mills/kWh for the once-through cycle. The recent in-house COGEMA fuel cycle comparisons show a very slight advantage of the reprocessing and recycling option over the direct disposal option. However fuel cycle economics are not the only consideration in the selection process.

It should be noted that at the NEA/IEA High Level Workshop (1986) on Nuclear Energy Prospects to 2000 and Beyond, the French paper on whether or not to reprocess (round table in Session II) emphasized the following two points:

- The risk of underestimation of costs is higher for direct storage of spent fuel than for reprocessing, only the latter solution having already been confirmed by industrial experience;

- Reprocessing prices have started to diminish and by 2000, when COGEMA reprocessing installations will be written off, reprocessing services prices will be lowered.

Finally, if account is taken of a significant rise in uranium prices the reprocessing option would lead to considerable savings, and uranium prices are expected to rise in the early to mid 90s.

2. Waste storage by category and hence by activity level is more rational from the management standpoint than final storage of spent fuels.

3. From the safety standpoint also this method is much more satisfactory.

Since the massive introduction of fast breeder reactors will not occur before the next century, plutonium will be available for 15 to 20 years for recycling in light water reactors. As reprocessing is regarded as inevitable (see points 1, 2 and 3) plutonium would seem to be a by-product of zero value. An economic comparison (uranium and enrichment savings are higher than the additional cost for fabricating plutonium fuel) shows the advantage of recycling plutonium as soon as possible. The conversion of Pu-241 into Am-241 makes plutonium unusable in thermal reactors in the event of extended storage. This economic comparison shows that the plutonium equivalent value is approximately FF 100 per g to FF 150 per g, so that if plutonium can be found at a lower price on the market, it would be worth purchasing for recycling.

After two recyclings, which would require about 20 years, about half the plutonium invested would be recovered, which would be used only in fast breeder reactors because of its isotopic composition.

JAPAN

Rationale for Promoting Reprocessing/Recycling

The establishment of the plutonium utilisation system, which also surpasses uranium utilisation in LWRs in terms of safety and economy, will be a long-range goal in Japan, with the object of realizing more efficient utilisation of uranium resources and improving the supply stability of nuclear power generation. In other words, following the basic strategy consisting of spent fuel reprocessing and utilisation of plutonium and recovered uranium, i.e., the "Reprocessing/Recycle Line", steady and stepwise development efforts will be made consistently.

Basic Approach for Utilisation of Plutonium

In principle, plutonium obtained by reprocessing of spent fuel will be utilised in FBRs, but it is presumed that a long time will be required before the practical use in FBRs.

Under these circumstances, the stepwise development of utilisation of plutonium will be realised under the following strategy.

The programme of the utilisation of plutonium in LWRs and in advanced thermal reactors (ATRs) will be promoted as soon as possible for the purpose of consolidating the wide-range technological system related to the utilisation of plutonium, which is indispensable in the future era of the FBRs, and of attempting to improve the overall economy of the nuclear fuel cycle. In this connection,

demonstration programmes related to the utilisation of plutonium in LWRs will be promoted in a steady way. On the other hand, the development of ATRs will be implemented through the execution of a demonstration reactor programme, and other related activities aimed at practical use.

Research and development on FBRs will be carried out concurrently with the aforementioned programmes. The basic philosophy in this connection will be to actively implement the programmes whose ultimate objective is to build up the system for the utilisation of plutonium by means of FBRs as a technological system surpassing the utilisation of uranium in LWRs, including economy and safety.

Promotion of Plutonium Utilisation

1. FBR

The construction of the prototype reactor "Monju" will be promoted with its criticality scheduled in 1992. On the other hand, the programme related to the demonstration reactor will be implemented with the target to start construction in the late 1990s.

Technological foundation will be consolidated by required R&D activities as well as the accumulation of the relevant experience related to the construction and operation of several FBRs, thereby aiming at the establishment of a technological system for utilisation of plutonium in FBRs in the period ranging from the 2020s to about 2030.

2. ATR

A 606 MWe capacity demonstration reactor will be constructed in Ohma-Machi, Aomori Prefecture, under the leadership of the private sector, with a mid-1990s target for its commissioning. The construction of subsequent reactors will be dealt with by taking into consideration such factors as the state of construction of the demonstration reactor, the economy of the ATR and the plutonium balance.

As for the prototype reactor "Fugen", it will be operated in the most efficient way as a prototype for the irradiation of nuclear fuel for the demonstration reactor, and further elevation of the reliability of the ATR.

3. LWR

In connection with the utilisation of plutonium in LWRs, a shift to commercial utilisation will be attempted via small scale and practical-use scale demonstration programmes.

The small-scale demonstration programme is carried out by loading a small number of MOX fuels in one pressurized water reactor (PWR) and one boiling water reactor (BWR). On the other hand, the practical-use scale demonstration programme will be implemented by assuming the ultimate loading of MOX fuel corresponding to one quarter of reactor core in one PWR and one BWR (above 800 MWe) respectively, with the target year scheduled for the first half of the 1990s. The programme as a whole will be implemented by aiming at realising the shift to commercial utilisation in the second half of the 1990s.

As for the scale of commercial utilisation, results of trial calculations by assuming a loading scale of MOX fuel on the order of one third core per reactor, indicate that it will be presumably possible to load 10 power plants of 1000 MWe class.

Promotion of Reprocessing

In principle, the reprocessing of spent fuel will be carried out in Japan. As for spent fuel exceeding the capacity of the domestically available reprocessing facilities, it will be properly stored and controlled until reprocessed.

The consignment of reprocessing abroad will be handled with care, by taking into consideration both the domestic and the international situation.

As for the plants for the reprocessing of spent fuel, measures will be taken to promote the stable operation of the Tokai Reprocessing Plant currently in operation, and also measures will be taken to promote the smooth construction and operation of the first private reprocessing plant, now being planned with an annual capacity of 800 tonnes, and commissioning scheduled for about the mid-1990s. As for the second private reprocessing plant, it is especially important to build the plant with further improved economy by domestic technology. Various measures will be implemented in a comprehensive way, with the plant start-up scheduled for about 2010.

Research and development on the reprocessing of FBR spent fuel, which will be the key to the nuclear fuel cycle in the FBR area, will be carried out in proper coordination with other R&D on the FBRs.

MOX Fuel Fabrication

In connection with MOX fuel the FBR prototype reactor and MOX fuel for the ATR demonstration reactor, measures will be taken to properly equip Power Reactor and Nuclear Fuel Development Corporation (PNC) so that it will be able to supply the fuel.

In connection with the MOX fuel for the FBR demonstration reactor, its supply will become possible by expanding the facilities of PNC. The concrete line of strategy regarding the nuclear fuel fabrication scheme will be defined in the early 1990s.

In connection with MOX fuel for the practical-use scale demonstration programme, aiming at utilisation of plutonium by means of LWRs, the uranium fuel suppliers currently in operation and PNC will cooperate in supplying the fuel by using the plutonium fuel production facilities of PNC through an expansion of the facilities, and other required measures.

In principle, the MOX fuel for full-scale utilisation of plutonium by means of LWRs will be handled by private enterprises. The concrete fuel fabrication scheme will be established in the early 1990s, at the latest.

SWITZERLAND

Status of Industry

There is no industrial activity in Switzerland itself in the field of uranium mining and milling, conversion, enrichment, fuel fabrication (uranium or MOX fuel) and reprocessing and there are no plans to develop such facilities. However, there are some R&D activities mainly in the field of fuel fabrication and Swiss Utilities are involved with uranium mining projects abroad. Therefore, the utilities are dependent on the supply of all fuel cycle services from abroad.

Industrial Framework, Current Practice, Future Plans

There is no official federal (governmental) policy on the use of plutonium and there are no provisions foreseen in the Swiss legislation to have such a policy. Consequently, it is fully up to the nuclear power plant operators what to do with the plutonium and to develop appropriate strategies.

The Swiss utilities have signed reprocessing contracts with BNFL and COGEMA and they have decided to recycle the uranium and the plutonium recovered from such reprocessing services in their own Light Water Reactors.

In the past part of the plutonium already separated from Swiss fuel under reprocessing contracts with COGEMA has been sold and part is now recycled by one utility under a MOX demonstration programme. In the 1990s larger quantities of plutonium will be recycled. The responsibility for the recycle is completely with the power plant operators, supported by the relevant licensing authorities.

Factors Influencing Policy

The spent fuel management policy adopted in Switzerland is based on reprocessing. The power plant operators firmly plan to recycle the plutonium in their own reactors aside from smaller quantities which may be supplied for breeder programmes or research as the case may be. By doing so, maximum utilisation of uranium and plutonium in spent fuel will be made, thereby achieving also diversification and taking advantage of the absence of plutonium in the high-level waste.

UNITED KINGDOM

Status of Industry

Reprocessing of irradiated fuel in the UK has been carried out since 1952 at BNFL's Sellafield site. The present Magnox reprocessing plant has been operating since 1964. Since the start of

operations, over 30 000 tonnes uranium of Magnox fuel has been reprocessed and the present plant with some refurbishment is expected to continue operation through to the end of the Magnox programme in the first decade of the 21st century. The THORP plant for the reprocessing of AGR and LWR oxide fuels has a design capacity of 1200 tonnes uranium per annum and is programmed for handover and subsequent operation in 1992. Plutonium and uranium are recovered from both these reprocessing operations in the form of PuO_2 and UO_3.

The recycle of plutonium in the fast reactor fuel cycle has been successfully accomplished in development facilities in the UK. The BNFL fuel fabrication plant at Sellafield has produced some 17 tonnes of mixed oxide pellets for fast reactor fuel for the prototype fast reactor (PFR) at Dounreay. However as part of European collaboration on fast reactors PFR pelleting and canning is now carried out at Cadarache (France) with final fuel assembly at Sellafield. Spent fast reactor fuel has been reprocessed by the UKAEA and subsequently refabricated by BNFL and re-irradiated, thus demonstrating the closed fuel cycle. Before embarking on a major fast reactor development, the UK Generating Boards (currently the CEGB and SSEB) will wish to be confident that the economics of commercial scale fast reactor fuel reprocessing will in the event lie close to the current planning assumptions. At present it is considered that a major commitment to fast reactor deployment would not take place until the second or third decade of the next century. Time therefore exists for the economics to be established.

The BNFL fuel plants at Sellafield, in addition to fabricating fast reactor fuel, have also produced some 3 tonnes of fuel at up to 7 per cent plutonium concentration for irradiation in various European thermal reactors during the 1960s. However during the 1970s the UK's thermal plutonium recycle experience involved no fuel manufacture and was limited to participation in several research programmes of which the EEC R&D programme between 1975 - 1979 was the most significant.

Over 15 000 tonnes of uranium recovered by reprocessing fuel from the Magnox reactors has been converted into UF_6 at BNFL Springfields and enriched in the BNFL Capenhurst diffusion plant and URENCO gas centrifuge plants. The enriched UF_6 was returned to Springfields for the manufacture of fuel and around 75 per cent of that fuel used to date has been produced from reprocessed uranium. The UK utilities plan to continue recycling Magnox depleted uranium through the AGR fuel cycle.

Institutional Framework

Apart from the utilisation of plutonium by the UKAEA in developing the PFR at Dounreay, UK policy to date has been to store the recovered plutonium for eventual use in future reactors. The amount of plutonium required for future fast reactor use is uncertain. It depends not only upon the extent and timing of commercial fast reactor deployment by the UK Generating Boards but also on the reactor and reprocessing plant designs and fuel cycle characteristics adopted. The extent of any commitment the UK might make under the European Fast Reactor Collaboration agreements will also have an effect.

Stocks of UK civil plutonium are increasing as spent Magnox fuel continues to be reprocessed, and this will be added to from the early 1990s onwards by the arisings from the reprocessing of spent AGR oxide fuel in THORP. At the end of the current reprocessing commitments involving completion of the Magnox programme and the 'baseload' component of THORP, the UK Generating Boards expect to have in store up to about 75 tonnes of plutonium.

The UK Generating Boards have examined other possible plutonium utilisation strategies involving recycling plutonium in thermal reactors which use oxide fuel. In conjunction with BNFL both the technical feasibility and the economics of the use of mixed plutonium and uranium oxide (MOX) fuel in the UK have recently been examined by the CEGB. A greater economic incentive to recycle plutonium in PWRs rather than AGRs has been identified. Taking into account the construction programme for the first PWR

in the UK, Sizewell B, and likely subsequent stations, it is not envisaged that plutonium recycle could be undertaken in the UK on any major scale before the turn of the century.

Future Plans

In respect of thermal MOX fuel BNFL are moving towards a position of being able to satisfy potential UK Generating Board's requirements and in addition to offer a service to overseas customers. During 1985 BNFL approved and commenced a development programme directed towards ensuring that they will be in a position to construct a commercial scale thermal reactor MOX fuel fabrication plant when market conditions justify it. For the present, BNFL, Belgonucléaire and COGEMA have reached an agreement relating to thermal MOX fuel which marks the commencement of a joint R&D programme on MOX fuels and allows BNFL access to COMMOX manufacturing capability. Plans envisage a BNFL operated UK thermal MOX fabrication facility starting up in the late 1990's as market demand dictates.

European Fast Reactor Collaboration envisages the utilisation of single fuel cycle facility for joint use by the partners to support the early demonstration of fast reactors. For fuel fabrication services the current CEA plant at Cadarache should be able to satisfy fast reactor requirements until commercial scale ordering commences. No fast reactor fuel reprocessing facility of sufficient size currently exists to satisfy demonstration reactor demands. The UKAEA/BNFL made a joint outline planning application in 1986 to permit the construction of such a plant at Dounreay given eventual agreement amongst the partners that a UK based plant should be developed. That application is under consideration.

The centrifuge enrichment process pioneered and used by URENCO is ideally suited to the re-enrichment of reprocessed uranium while maintaining segregation from other types of fuel. URENCO plan commercial scale facilities for enrichment of reprocessed uranium in the 1990s as the output from major reprocessing plants becomes available. On the same timescale, BNFL is planning to offer a commercial service for the manufacture of ex-oxide uranium fuel.

UNITED STATES

Plutonium is generated during the operation of commercial nuclear power reactors and is discharged in spent reactor fuel at a rate of about 250 kilograms per year per gigawatt of installed capacity. By the turn of the century, the projected installed nuclear capacity in more than 20 non-communist countries will be about 350 gigawatts, and the amount of plutonium discharged in spent fuel will be nearly 100 tonnes annually. However, the amount of separated plutonium from spent fuel will be limited by the availability of reprocessing capability. It is estimated that the cumulative total of fissile plutonium separated by the year 2000 will be well under 100 tonnes.

Plans for the disposition of plutonium vary widely from country to country because of differing national views and priorities for energy security, nuclear waste management, and industrial development. Plutonium can be used as a fuel to support energy security objectives. However, its use requires large capital investments and a skilled work force to build and operate commercial facilities to separate plutonium from spent fuel and fabricate plutonium-bearing fuels for use in fast breeder reactors (FBR) or thermal recycle light water reactors (LWR). Because of this, some countries in Europe and Japan have chosen to pool their technical and economic resources, and some have chosen to purchase services as an alternative to indigenous development.

Further, since a few kilograms of separated plutonium are sufficient for use in nuclear explosives, non-proliferation considerations weigh heavily on commercial and governmental decisions regarding civil plutonium use. For example, in order to prevent diversion, effective national physical protection and international safeguards systems must be in place to assure that plutonium is used only for intended peaceful purposes. Also, the multilateral Nuclear Suppliers' Guidelines call for "restraint in the transfer of sensitive facilities, technology, and weapons-usable material," which applies to plutonium.

The United States began the development of commercial plutonium technologies more than 30 years ago. While government-supported research and development (R&D) on thermal recycle was essentially finished by 1970, major industrial programmes were initiated in 1967 and culminated in demonstration programmes using plutonium/uranium (mixed-oxide - MOX) fuel in commercial LWRs.

In 1976, the US Government declared a moratorium on the reprocessing of commercial spent nuclear fuel that had the effect of placing on hold the further commercialisation of plutonium use technologies in the United States. President Reagan's Nuclear Energy Policy Statement of October 1981 stated that the U.S. Government's domestic policy is to support private investment for reprocessing of LWR spent fuel by removing unnecessary regulatory impediments and by creating stable, long-term conditions under which commercial reprocessing could be viable. But, the private sector is expected to take the lead in developing commercial reprocessing services. At the present time, U.S. industry has demonstrated little or no interest in commercial reprocessing due to the lack of any clear economic incentives, decreased demand for recovered plutonium, and regulatory uncertainties. Thus, the US Department of Energy's current programme does not include funds to support technical development in the area of reprocessing of spent, commercial LWR fuel and will not consider engaging in such efforts until such time as there is an industry commitment to private reprocessing.

The President's Nuclear Energy Policy Statement also called for the Department of Energy, working closely with industry and State governments, to proceed swiftly towards deployment of means of storing and disposing of commercial, high-level radioactive waste. With the passage of the Nuclear Waste Policy Act of 1982, funding mechanisms, and construction milestones were established aimed at the completion of an operational repository for high-level nuclear waste and spent nuclear fuel by the turn of the century. With respect to disposal of spent nuclear fuel, the respository is to be designed to permit the retrieval of such fuel for an appropriate period of time, for any reason pertaining to public health and safety or the environment, or for the purpose of the economically valuable contents of such spent fuel. Without domestic commercial reprocessing and in the current economic and energy resource environment, detailed technical designs have focussed on spent fuel as the waste form leading to the direct disposal of spent fuel without separating uranium and plutonium.

Although US industry has no plans to recycle separated plutonium in commercial LWR's, the US Government continues to be interested in plutonium utilisation in liquid metal reactors both indigenously and abroad. The U.S. R&D programme is cast along the following broad lines: Extend, in the short term, the burn-up of LWR fuel, develop a US Nuclear Regulatory Commission certified, low capital cost, passively safe Liquid Metal Reactor (LMR) for intermediate term applications and maintain the option to deploy a breeder in the long term.

Extending the burn-up of LWR fuel increases the in situ utilisation of plutonium, reduces fuel costs, and decreases the number of spent fuel assemblies that must be stored or reprocessed at a later date. While primary objectives of the LMR programme are passive safety and reduced capital cost through factory manufacture, current designs can achieve a breeding ratio that will more than make up for reprocessing and refabrication losses (e.g. 1.1 to 1.2).

Internationally, the United States has acknowledged the close relationship between peaceful nuclear co-operation and effective non-proliferation policies. US policy recognises that a number of countries with advanced nuclear power programmes and sound non-proliferation credentials are counting on plutonium to supply a significant portion of their energy needs and that international co-operation is

necessary to maintain effective non-proliferation controls. However, it also recognises the proliferation risks associated with the capability for the separation of plutonium from spent fuel.

The OECD countries with advanced nuclear programmes have been co-operating for some time to address the resource, technical and economic challenges posed by plutonium use facilities for IAEA safeguards and for further developing the physical security systems needed to prevent the theft and diversion of sensitive nuclear materials from facilities and during transport. In addition, the Convention on the Physical Protection of Nuclear Materials, which entered into force on 8th February 1987, provides a framework for enhancing international coordination and co-operation to assure the protection of international shipments of nuclear materials.

As the commercial use of plutonium increases, it will be important to use existing and additional cooperative approaches to assure that non-proliferation measures evolve that do not adversely affect commercial activities, yet which provide a high degree of effectiveness in ensuring peaceful uses of such nuclear material.

For developing countries embarked or about to embark on nuclear power programmes, the fundamental issues of economics, waste management, energy, and national security need to be addressed from their own perspectives. For economic conditions that are likely to be observed for the foreseeable future, studies indicate that the long-term storage and/or direct disposal of spent fuel would be less costly than developing indigenous reprocessing and plutonium fabrication facilities and breeder reactors. Thus, bilateral co-operation, such as that called for under Section 223 of the Nuclear Waste Policy Act, can help support the development of non-sensitive technologies for managing spent fuel and the plutonium contained therein. Such co-operation can help instill confidence that there are viable technical alternatives to reprocessing to solve the waste management problem. At the same time, it can provide one possible direction for a nuclear power programme that addresses energy security interests, is economically sound, and deals with proliferation concerns.

COMMISSION OF THE EUROPEAN COMMUNITIES

In November 1984, the Commission of the European Communities adopted a document on the nuclear industries in the community. This "Illustrative nuclear programme", better known as the "PINC" (from "Programme Indicatif Nucléaire pour la communauté") was published in July 1985 [COM(85)401 final].

In the document the Commission describes and analyses the situation of the nuclear industry in the Community and sets out the prospects of its medium- and longer-term development. It concludes that nuclear energy should produce about 40 per cent of Community electricity in 1995 and that its share in electricity production should increase to around 50 per cent around the turn of the century. The Commission then made a series of recommendations as to what needed to be done to achieve these objectives.

Concerning plutonium, the Commission made the following observations:

All uranium-fuelled nuclear power stations, whether the uranium is natural or enriched, produce plutonium within the fuel elements. This is the case, in particular, with PWRs and FBRs, on which the development of nuclear power in the Community will henceforth be mainly based.

All the Member States - and the Community itself - have chosen the option of reprocessing spent fuel elements which, among other advantages, possesses that of recovering the plutonium by means of which the FBRs can make use of all the uranium's energy content.

Although there is a certain measure of interdependence between the implementation of programmes for the construction and operation of nuclear power stations and that of the reprocessing plant, it is not possible to ensure that the flow of available plutonium will correspond exactly to the demand arising from the FBR programme. It is currently estimated that the FBR objective proposed for the Community will absorb only part of the plutonium to be produced by the reprocessing plants between now and the end of the century.

Temporary storage of the excess plutonium can be considered, although it gives rise to a technical problem as a result of the radioactive decay characteristics of one of the plutonium isotopes.

This characteristic provides an additional reason for seriously considering another use of plutonium, namely, in reactors of the present generation, i.e. by *plutonium recycle.*

This technique, which has reached the stage of industrial application in the Community, is certainly not as efficient as the FBR technique in extracting energy from uranium, but it does enable substantial savings to be made in uranium consumption and in enrichment services.

Finally, only part of the plutonium used in this way is consumed, so that thermal recycling will not compromise subsequent development of the FBR concept.

Intensified intra-European co-operation in this field would make it possible to obtain the maximum from all the technological experience acquired by the various Community partners and from already existing investments.

The Commission therefore concluded that "the development and fabrication of uranium and plutonium mixed-oxide fuel elements should be vigorously pursued, first with a view to promoting commercial recycling in LWRs of the materials resulting from reprocessing uranium and plutonium, and later with the purpose of optimising the entire FBR fuel cycle. In this connection, close co-operation between designers, fuel manufactures, reprocessors and electricity producers should be encouraged".

Annex G

EQUIVALENT PLUTONIUM

The equivalence factors by which each Pu isotope must be adjusted to deduce an "equivalent Pu" (= Pu_{eq}) expressed either as an equivalence to Pu-239 or to U-235 are to be defined in such manner that, whatever the isotopic composition of a given Pu, this Pu_{eq} enables the MOX fuel to:

- reach the same reactivity lifetime,
- achieve the same discharge burn-up (i.e. produce the same energy),
- maintain similar local power peaking levels within the fuel assembly and within the reactor core, throughout the residence time of the fuel in the reactor,
- keep the safety related fuel parameters almost unaffected.

As a result, the value of these equivalence factors depends in fact on:

- the reactor type: FBR or PWR, BWR, ...
- the Pu isotopic composition,
- the MOX fuel fraction in the core,
- the fuel assembly design: all-Pu, Pu-island ...
- the in-core fuel management,
- the discharge burn-up,
- the calculation methodology.

These equivalence factors must therefore be calculated for each particular case.

As an illustration, Table G.1 provides indicative values for such factors when expressing each isotope in relation to Pu-239:

Table G.1

INDICATIVE EQUIVALENCE FACTORS

	LWR	FBR (Super-Phenix)
U-235	+ 0.8	+ 0.8
Pu-238	- 1.0	+ 0.44
Pu-239	+ 1.0	+ 1.0
Pu-240	- 0.4	+ 0.14
Pu-241	+ 1.3	+ 1.5
Pu-242	- 1.4	+ 0.037
Am-241	- 2.2	- 0.33

For all practical LWR purposes, this can then be expressed in terms of an "equivalent Pu-239" formula for a given Pu:

$$Pu_{eq} = - Pu8 + Pu9 - 0.4\ Pu0 + 1.3\ Pu1\ (1 - 0.00013 \cdot \Delta t) - 1.4\ Pu2 - 2.2\ (A1 + 0.00013\ Pu1 \cdot \Delta t)$$

where:

- Pu8 is the weight of Pu-238 in the Pu
- Pu9 is the weight of Pu-239 in the Pu
- Pu0 is the weight of Pu-240 in the Pu
- Pu1 is the weight of Pu-241 in the Pu
- Pu2 is the weight of Pu-242 in the Pu
- A1 is the weight of Am-241 in the Pu

- all of them as measured (or otherwise determined) at a time t_o

- $\Delta t = t\text{-}t_o$ is the time in days elapsed between the isotopic composition measurement (or determination) and the date at which the equivalence is sought.

Similarly, the formula applicable to a given LWR MOX fuel would be:

$$Pu_{eq} = 0.8\ U5 - Pu8 + Pu9 - 0.4\ Pu0 + 1.3\ Pu1\ (1\text{-}0.00013 \cdot \Delta t) - 1.4\ Pu2 - 2.2\ (A1 + 0.00013\ Pu1 \cdot \Delta t)$$

where:

- U5 is the weight of U-235 in the fuel
- the other symbols have the same meaning as here above, but with reference to the fuel rather than to the Pu.

Annex H

FUEL COST CALCULATIONS - METHODS, ASSUMPTIONS AND BACK-UP DATA

1. Fuel Cycle Leads and Lags

1.1 Lead times for UO_2 fuel and MOX fuel

Lead times for procurement of enriched UO_2 fuel are assumed to be 6 months for fabrication, 12 months for enrichment, 18 months for conversion and 24 months for purchase of natural uranium, all measured from the time fuel is loaded into the reactor (see Figure 16a of the main report, and Table H.1).

In the previous study (4) 21 months was assumed as the reference lead time for purchase of natural uranium. The other lead times are the same as the previous reference values.

The lead time for MOX fabrication is assumed to be the same as that of UO_2 fabrication, i.e. 6 months (Figure 16b of the main report and Table H.1).

1.2 Time profile of spent fuel processing, MOX use and waste disposal

(a) In case of spent fuel reprocessing

Spent UO_2 fuel discharged from the reactor is stored for cooling for 2 years at the reactor site (Figure 16b of the main report) and then transferred to the reprocessing plant. Following 2 years cooling at the reprocessing site, spent fuel is reprocessed. Recovered plutonium is fabricated to MOX fuel and charged to the reactor 2 years after reprocessing, in accordance with the neutronics calculations. Waste from reprocessing is stored for 35 years, and then disposed of.

In the previous study (4) it was assumed that the spent fuel cooling time was 5 years (2 years at the reactor and 3 years at the reprocessing site), and the storage period of reprocessing waste was 35 years. In this study, the spent fuel cooling period is assumed to be 4 years so that time period from spent fuel discharge to disposal of waste is 39 years.

All costs and credits are discounted to the date of MOX fuel charge to the reactor so that lead times for reprocessing and uranium credit are assumed to be 2 years and lag time for reprocessing waste disposal is assumed to be 33 years (i.e., 33 years after the date of loading fuel into the reactor).

(b) In the case of spent fuel disposal

In the case that spent fuel is not reprocessed (Figure 16c of the main report), it is assumed to be stored for 2 years at the reactor site and then transferred to interim storage where it is held for 37 years and then disposed of (i.e. directly equivalent to waste disposal in (a) above. If the spent fuel disposal and reprocessing waste disposal, described above, are assumed to take place after identical delays following the removal of spent uranium fuel from the reactor, payment for spent fuel storage for 37 years is assumed to be made 4 years prior to the charge of MOX fuel to the reactor.

Payment for spent fuel disposal is made 33 years after the fuel charge to reactor, i.e., at the same time as for reprocessing waste disposal.

Table H.1

BASIC ASSUMPTIONS USED IN COST CALCULATIONS

Tails assay for enrichment	0.225 %
Lead time [a] [b]	
Uranium Cycle	
Uranium purchase	24 M
Conversion	18 M
Enrichment	12 M
Fabrication	6 M
Reprocessing Cycle	
Reprocessing	24 M
Waste disposal	at 35 years after reprocessing (33 years after loading MOX fuel to reactor)
Non-Reprocessing Cycle	
SF interim away from reactor storage	48 M (37 yr storage)
SF Condition/Disposal	at time after 37 yr storage of SF (33 years after MOX could have been loaded into reactor)
Recovery Factor [b]	
Conversion	99.5 %
Fabrication	99 %
Reprocessing	98 %
Others	100 %
Discount rate [b]	5 % (10 % variant)
Uranium credit [b]	80 % of the cost of equivalent new uranium and enrichment

a. Lead time specifies the date at which a payment for a component of fuel cycle occurs prior to the date of loading fuel into reactor (see Figure 13).

b. These are basically consistent with the reference figures used in the previous report (4).

(c) Sample calculation

Based on the above assumptions, an example of the discounted cost calculation is shown in Table H.2. The figures relate to the production of 1 kg of UO_2 or MOX fuel for 33 000 MWd/tonne burn-up and require the reprocessing of 5.38 kg HM of spent UO_2 fuel (see Table H.3) and corresponding credits (Table H.5).

2. Value of Recovered Uranium

2.1 *Definition*

The value of recovered uranium is defined as that which results in equal costs for enriched uranium produced from natural uranium (NU) and from recovered uranium (RU).

Cost of enriched uranium from NU ($/kg)

$$= C_{U308} \cdot F_1 + C_{UF6} \cdot F_1 + C_{SWU} \cdot S_{NU} + C_{UO2} \quad (1)$$

Cost of enriched uranium from RU ($/kg)

$$= C_{REC} \cdot F_2 + (C_{SWU} + \Delta C_{SWU}) \cdot S_{RU} + (C_{UO2} + \Delta C_{UO2}) \quad (2)$$

Recovered uranium price; C_{REC}, i.e., value of recovered uranium, is then calculated as follows :

$$C_{REC} = C_{U3O8} \cdot F_1/F_2 + C_{UF6} \cdot F_1/F_2 + C_{SWU} (S_{NU} - S_{RU})/F_2 - \Delta C_{SWU}/F_2 - \Delta C_{UO2}/F_2 \quad (3)$$

where,

C_{U3O8} ; price of natural uranium ($30/lb U3O8 = $78/kg U)

C_{UF6} ; price of UF_6 conversion ($7/kg)

C_{SWU} ; price of enrichment ($100/SWU)

ΔC_{SWU} ; premium for enrichment of RU ($10/SWU) This small but non-negligible factor is not carried through into the subsequent calculations.

C_{UO2} ; price of UO_2 fuel fabrication ($200/kg)

ΔC_{UO2} ; premium for UO_2 fuel fabrication ($30/kg)

F_1 ; natural uranium requirement for 1 kg of enriched uranium

F_2 ; recovered uranium requirement for 1 kg of enriched uranium

S_{NU} ; separative work for 1 kg of enriched uranium from NU

S_{RU} ; separative work for 1 kg of enriched uranium from RU

Figures in brackets above are illustrative costs adopted in this study.

Table H.2

CALCULATION OF DISCOUNTED COSTS FOR EACH COMPONENT TO PRODUCE 1 KG UO_2 OR MOX FUEL (33 000 MWd/t)

Component	Lead Time (year)	Discount Factor (DF)	1 - Recovery Factor (%)	Discounted Costs
UO_2 Fabrication	0.5	1.025	1.0	1 kg x 1.01 x \$200/kg x DF (Discount Factor) = \$207
Enrichment	1.0	1.05	-	Separative work for 1 kg of 3.25% U-235 enriched fuel; 4.564 SWU 1.01 kg x 4.564 SWU/kg x \$100/SWU x DF = \$484
UF_6 Conversion	1.5	1.076	0.5	Natural uranium requirement for 1 kg of 3.25% U-235 enriched fuel; 6.224 kg 1.01 kg x 1.005 x 6.224 x \$7/kg x DF = \$48
U_3O_8	2.0	1.103	-	6.32 kg (1.01 kg x 1.005 x 6.224) x A x DF = 6.97 kg x A dollars. A = uranium price (\$/kg)
MOX Fabrication	0.5	1.025	1.0	1 kg x 1.01 x \$800/kg x DF = \$828
Reprocessing	2.0	1.103	2.0	5.38 kg x \$$e_1$/kg x DF = \$5.93 e_1
Reprocessing Waste Disposal	-33.0	0.200	-	5.38 kg x \$$e_2$/kg x DF = \$1.08 e_2
Spent Fuel Storage	4.0	1.216	-	5.38 kg x \$$d_1$/kg x DF = \$6.54 d_1
Spent Fuel Disposal	-33.0	0.200	-	5.38 kg x \$$d_2$/kg x DF = \$1.08 d_2

- d_1 and e_1 are the present worth costs of spent fuel storage and reprocessing respectively at the time fuel is fed to the store or plant.
- d_2 and e_2 are the present worth costs of disposal of spent fuel and high level fission product reprocessing wastes respectively at the time of disposal.
- The overall costs (d_1+d_2) and (e_1+e_2) need to cover fuel and waste conditioning and the costs of any other waste streams.

Table H.3

REPROCESSING REQUIREMENTS FOR FABRICATING 1 KG HM OF MOX FUEL

- parameter: spent fuel cooling period -

Burn-up of MOX Fuel (MWd/t)	Spent Fuel[1] Cooling Period (year)	Amount of SF[1] Reprocessed (kg HM)	Plutonium Contained in SF[1] (g Pu_f)	Recovered Plutonium (g Pu_f)	Mox Fuel Fabricated (kg HM)
33 000	4	5.38	36.8	36.0	1.0
	10	5.53	37.5	36.8	1.0
43 000	4	6.17	42.2	41.4	1.0
	10	6.34	43.0	42.1	1.0
53 000	4	7.43	50.8	49.8	1.0
	10	7.61	51.6	50.6	1.0

1. Spent UO_2 fuel with 33 000 MWd per tonne burn-up, "Pu 33" is used for MOX fuel.

2. Values are based on Tables 9 and 12A, main report, allowing for processing efficiencies.

Table H.4

REPROCESSING REQUIREMENTS FOR FABRICATING 1 KG HM OF MOX FUEL

- parameter: MOX fuel burn-up -

Burn-up of MOX Fuel (MWd/t)	Pu used in MOX Fuel	Amount of SF[3] Reprocessed (kg HM)	Enrichment of Recovered Uranium (% ^{235}U)	Recovered Plutonium (g Pu_f)	MOX Fuel Fabricated (kg HM)
43 000	Pu 33 [1]	6.17	0.92	41.4	1.0
	Pu 43 [2]	6.09	0.80	44.9	1.0
53 000	Pu 33	7.43	0.92	49.8	1.0
	Pu 43	7.31	0.80	53.9	1.0

1. Pu from 33 000 MWd per tonne spent UO_2 fuel.
2. Pu from 43 000 MWd per tonne spent UO_2 fuel.
3. 4 years cooling of spent fuel.

Table H.5

CALCULATION OF DISCOUNTED COSTS FOR EACH COMPONENT - URANIUM CREDITS LINKED TO SPENT FUEL REPROCESSED TO PRODUCE PLUTONIUM FEED FOR 1 KG OF MOX FUEL

Component	Lead Time (year)	Discount Factor (DF)	Loss (%)	Discounted Costs
Credit of Recovered Uranium	2.0	1.1025	2.0	- Mass of recovered uranium from 5.38 kg of spent fuel; 5.38 x 0.99 x 0.98 = 5.22 kgU where, 0.99 = ratio of uranium contained in spent fuel (Table 9, main report) 0.98 = reprocessing recovery factor (Table H.1)
				- U-235 enrichment of recovered uranium = 0.92 % (from Table 9, main report)
(1) SWU Credit				- Separative work for 1 kg of 0.92 % U-235 enriched uranium = 0.2395 SWUs 5.22 kg x 0.2395 SWU/kg x $100/SWU x DF = $138 - 80 % of value = $138 x 0.8 = $110
(2) Conversion Credit				- 5.22 kg of recovered uranium is equivalent to 7.50 kg of natural uranium, taking into account 0.5 % loss in conversion. 7.50 kg x $7/kg x DF = $58 - 80 % of value = $58 x 0.8 = $46
(3) Natural Uranium Credit				- Cost of 7.50 kg of natural uranium 7.50 kg x A x DF = 8.27 kg x A dollars, A = uranium price ($/kg) - 80 % of value = 8.27 x A x 0.8 = 6.62 kg x A dollars

2.2 *Effect of U-236*

U-236 is a neutron poison in a reactor core and some allowance must be made for its presence when recovered uranium is used in the manufacture of new fuel.

An example of the additional U-235 enrichment required to allow for negative reactivity effects of U-236 is shown in Annex 10 of the 1987 Yellow Book (1) as follows:

$$\frac{X_e}{x_{RU}} = 0.75 \frac{a_o + e_a}{a'}$$

$$e_a = 0.28X_e$$

where X_e = U-236 concentration in re-enriched fuel

x_{RU} = U-236 concentration in recovered uranium (0.41 per cent)

a_o = U-235 concentration in fresh fuel without U-236 (3.25 per cent)

e_a = additional concentration of U-235 required to allow for U-236

a' = U-235 concentration in recovered uranium (0.92 per cent)

Figures in brackets above come from this study's neutronics calculations (Table 9, main report).

From the above two equations, X_e and e_a are calculated to be 1.17 per cent and 0.33 per cent, respectively. 3.25 per cent enriched uranium without U-236 is equivalent to 3.58 per cent enriched uranium with 1.17 per cent of U-236.

F_2 and S_{RU} in equation (3) are calculated and shown in Table H.6.

2.3 *Effect of gamma radiation*

Recovered uranium contains high energy gamma-emitting nuclides so that the fabrication of recovered uranium requires use of some screening to protect the workforce. This will result in an increase in fabrication costs of UO_2 fuel. A \$30 per kg premium for fabrication (ΔC_{UO2}) is suggested (Section 2.5.4.5). Similarly a \$10/SWU premium (ΔC_{SWU}) is considered appropriate for enrichment of recovered uranium (Section 2.5.4.4).

2.4 *Results*

The value of recovered uranium is reduced to 73 per cent to 82 per cent (Table H.7) of the cost of equivalent new uranium and enrichment to take into account the allowance for U-236, depending on the premiums for enrichment and fabrication described in Sections 2.2 and 2.3 of this Annex. Tables H.6 and H.7 set out the numerical values for the calculated example.

Table H.6

URANIUM AND SEPARATIVE WORK REQUIREMENT

	Enriched Uranium from Natural Uranium	Enriched Uranium from Recovered Uranium	
		No Allowance for U-236	Allowance for U-236
Feed Enrichment	0.71 % (1)	0.92 % (2)	0.92 % (2)
Tails	0.225 %	0.225 %	0.225 %
Product Enrichment	3.25 %	3.25 %	3.58 % (3)
Uranium Requirement for 1 kg Enriched Uranium	F_1 = 6.224 kg	F_2 = 4.353 kg	F_2 = 4.827 kg
SWU Requirement for 1 kg Enriched Uranium	S_{NU} = 4.564 SWUs	S_{RU} = 3.521 SWUs	S_{RU} = 4.105 SWUs

1. U-235 enrichment in natural uranium.
2. U-235 enrichment in recovered uranium.
3. U-235 enrichment to overcome the negative reactivity effect of U-236.

In this evaluation the conversion cost of recovered uranium to UF_6 is assumed to be included in reprocessing cost. If this is not the case, the additional cost for conversion to UF_6 leads to a further reduction in the value of recovered uranium. The effect is only of the order of 5 per cent however.

3. Calculation of Plutonium Values

Plutonium value is defined as the plutonium price, at which the fuel cost of the plutonium cycle is equal to the cost of uranium cycle. This is the so-called indifference value of plutonium.

In this calculation, plutonium value is approximated by equalizing the costs of uranium fuel elements and mixed oxide fuel elements designed to attain the same burn-up, since differences in back-end cost for the two fuels will not be large provided spent MOX fuel is not recycled further.

An example of the calculation for $80 per kg uranium is shown in Table H.8.

Table H.7

CALCULATED VALUE OF RECOVERED URANIUM

	Value of Recovered Uranium	Ratio
No Allowance for U-236 and no Premium for Fabrication	$145/kg[1]	100 %
With Allowance for U-236 and No Premium for Fabrication	$119/kg	82 %
With Allowance for U-236 and Premium for Fabrication	$113/kg	78 %
With Allowance for U-236 and Premiums for Fabrication and Enrichment	$106/kg	73 %

1. 100 per cent of the cost of new uranium and enrichment.

4. Calculation of the Break-Even Prices for MOX and Uranium Fuels

For this study a break-even price is defined as that price for a specified fuel cycle stage which results in equal costs for uranium fuel equilibrium reloads and MOX fuel reloads.

4.1 When Plutonium is already paid for

In the case of plutonium whose recovery costs have been paid or have been committed so that it has a zero monetary value attached to it by the owner (i.e. it is effectively "free") the break-even uranium price is that price at which the cost of 1 kg of enriched uranium oxide fuel exactly equals a technically equivalent kg of MOX fuel. It is determined solely by the fabrication costs of MOX fuel and the conversion, separative work and fabrication costs of uranium fuel, since the back-end costs for both fuels can be taken to be the same and the plutonium and depleted uranium feed for MOX are free. In the nomenclature of Figure H.1, for break-even: $a + b + c = h$, or, allowing for the lead times in Table H.1 with a discount (compounding) factor j: $aj^2 + bj + cj^{0.5} = hj^{0.5}$.

Table H.8

DISCOUNTED COSTS[1] AND PLUTONIUM VALUE

Component	Unit Cost (Reference)	Cost of UO_2 Fuel[2] ($/kg)	Cost of MOX Fuel[3] ($/kg)
Uranium	$80/kg	544	-
Conversion	$7/kg	48	-
Enrichment	$100/SWU	484	-
UO_2 Fabrication	$200/kg	207	-
MOX Fabrication	$800/kg	-	828
Cost excluding 36 g Pu_f plutonium [4]	-	1283	828
Indifference value of 36 g Pu_f	-	-	455
Indifference value of 1 g Pu_f	-	-	12.5

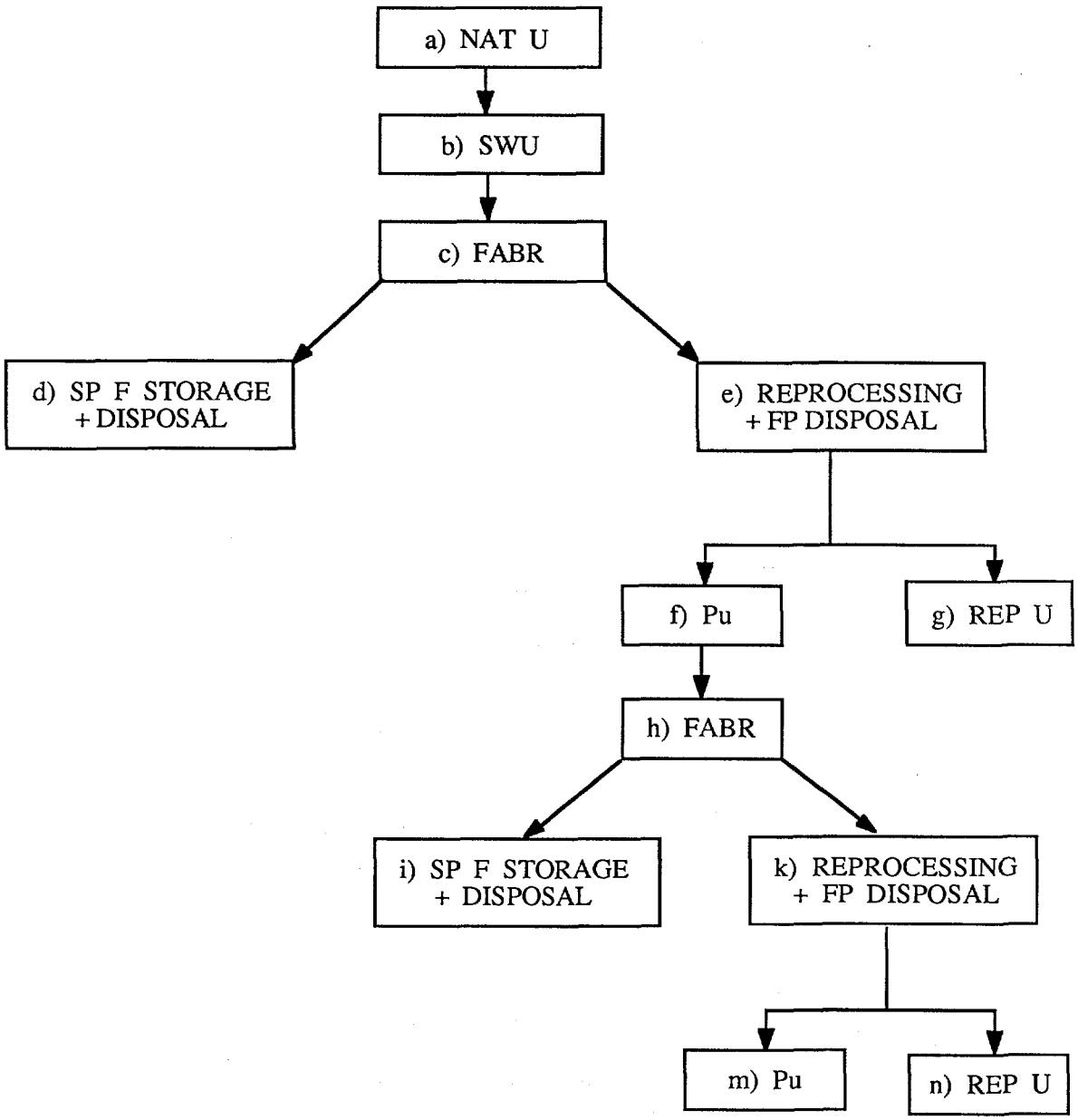
1. Discounted cost at 5 per cent discount rate.
2. UO_2 fuel with 33 000 MWd per tonne.
3. Using depleted uranium matrix.
4. Pu requirement for 1 kg of MOX fuel with 33 000 MWd per tonne: 36 g Pu_f. Lead time for payment for plutonium is assumed to be same as MOX fabrication i.e., 6 months prior to the loading.

4.2 When Plutonium pays for its recovery

In the case of plutonium charged at its recovery cost, however, the costs of reprocessing uranium fuel and disposal of its reprocessing wastes are additional charges to the MOX fuel, offset by savings on avoidance of spent uranium fuel storage, conditioning and disposal, and the appropriate credit for the recovered uranium (para 2.6.2.2). The situation is complicated further if the MOX fuel itself is to be reprocessed. This illustration ignores this possibility.

Costs are calculated for 1 kg of uranium fuel or technically equivalent MOX fuel, both for equilibrium batch reloads. The additional charges, savings and credit - the net additional charge - are derived from the amount of spent UO_2 fuel (Zkg) required to provide a sufficient amount of plutonium for fabricating the 1 kg HM of MOX fuel. In the simplified terms of Figure H.1. for break-even: $a + b + c + d = Ze - Zd + h + i - Zg$.

Figure H. 1
SIMPLIFIED STAGE COSTS FOR UO_2 AND MOX FUELS



Note : *a* to *n* are unit stage costs in $ / kg hm (or SWU) for the stages shown.

For simplicity uranium price *(a)* is taken to include conversion costs.

SP F = spent fuel ; FP = fission products.

Appendix 1 to this Annex expands on this simple formula and introduces the relevant discounting factors. It shows that for thermal MOX fuel paying is own plutonium recovery costs to be economically attractive

$$(e - d)j^2 \leqslant f + g \qquad (4)$$

where the j^2 term arising from the illustrative 2 year delay between spent fuel arrival at the reprocessing site and plutonium and uranium recovery.

The derivation of f is described in Section 3 and g in Section 2 of this Annex. Both are dependent on the costs of the front-end stages of the fuel cycle. Values of (f + g) are shown in Table H.9 for varying values of uranium price, enrichment and fabrication costs.

Table H.9

TOTAL Pu and U CREDITS

(once-through MOX and depleted U based MOX fuel case)

Uranium Price	Separative work cost	MOX Fabrication cost	f	g	f + g
$/kg	$/SWU	$/kg	$/kg HM initial fuel		$/kg HM initial fuel
50	100	800	46	74	120
80*	70	1000	19	110	129
	100	800	83	113	196
	130	700	129	116	245
110	100	800	121	152	273

UO_2 fabrication cost = $200 per kg.

* To conform with definition of uranium price in equation 3, Section 2.1, and hence with Table H.7, the g-values were calculated for a U_{nat} price of $78 per kg U instead of $80 per kg U.

It can be seen from Table H.9 and equation (4) that the differential cost between reprocessing including reprocessing waste conditioning and disposal (e) and spent fuel storage, conditioning and disposal (d) for break-even can vary considerably depending on uranium price, MOX fabrication costs and enrichment costs in the future. (Note both d and e are discounted present worth costs to a base date four years after spent UO_2 fuel leaves the reactor and four years prior to recycle of recovered plutonium in the illustration used here).

The break-even point would be different in the case where MOX fuel was co-processed with uranium oxide due to the changed composition and quantities of recovered plutonium and uranium per kg of mixed

fuels (MOX and UO_2) reprocessed. In general the credits (f and g) would be larger due to the higher fissile plutonium content of the mixture and the break-even differential would also be larger. Thus if MOX were coprocessed with UO2 fuel in the ratios described in Annex D only 4 kg of spent fuel has to be reprocessed to produce the 36 g of fissile plutonium needed per kg of MOX as compared with 5.4 kg when spent uranium is reprocessed alone. The plutonium credit per kg HM of initial fuel in Table H.9 would increase by 35 per cent in the illustrative case for $80 per kg U.

The substitution of the zero valued depleted uranium, used in the above examples for MOX production, by reprocessed uranium priced at its equivalence value or natural uranium at its market price, has little effect on MOX costs. This is due to the fact that depleted uranium has a very small equivalent value, whilst reprocessed uranium and plutonium have both been valued as uranium-235 substitutes in PWR fuel. The credited value of reprocessed uranium can therefore be obtained either by re-enrichment and recycle in uranium oxide fuel or by direct use in MOX. In principle the latter should be slightly more beneficial because the extra costs of uranium fuel fabrication and re-enrichment due to the radioactivity of reprocessed uranium, and the extra enrichment needed to compensate for uranium-236 accumulation on re-enrichment, are avoided.

The calculated values for the illustrative case would support that 1 kg of reprocessed uranium with an equivalence value of around $110 would save 8 g of fissile plutonium valued at $100 (in a total fabricated MOX fuel costing $1 300 per kg HM). Similarly 1 kg of natural uranium costing $78 can save 5.4 g of fissile plutonium valued at $67. The small deviations arise mainly from the zero valuation of depleted uranium.

The use of reprocessed uranium in MOX fuel produced using free plutonium also releases plutonium for further MOX manufacture and this too enables the equivalent value of the uranium to be regained.

The break-even differential will however be influenced by the phasing of fuel-cycle stages due both to the discounting effects and to the consequences of plutonium decay (see Table H.3). Table H.9 is based on an 18-month delay between separation of plutonium from spent fuel and its fabrication into MOX fuel. Delays in re-use will in general reduce plutonium and uranium values, although this could be offset if front-end costs for uranium fuel were increasing.

5. Calculation of Fuel Cost per KWh

The fuel cost per kWh is calculated by dividing the discounted cost of the fuel by the discounted electricity generated from the equilibrium batch of fuel.

Discounted electrical outputs used in the calculation of fuel costs per kWh are shown in Table H.10.

6. Annual Reload Batch Cost Calculation

MOX/UO_2 reload fuel consists of 30 per cent of MOX fuel and 70 per cent of UO_2 fuel with the same design burnups.

Annual requirements of reload fuels are assumed to be as follows:

33 000 MWd per tonne : 1/3 core = 24.0 tonnes HM per year
43 000 MWd per tonne : 1/4 core = 18.5 tonnes HM per year
53 000 MWd per tonne : 1/5 core = 14.8 tonnes HM per year

Table H.10

DISCOUNTED ELECTRICAL OUTPUT (KWh/kg) AS A FUNCTION OF BURN-UP

Burn-up (MWd/t)	Amount of Electricity (1) (kWh/kg)	In-Core Residence Time(2) (years)	Discount rate (%)	Discount Factor(3)	Discounted Electricity (kWh/kg)
33 000	261,360	3.00	5	0.9303	243,143
			10	0.8697	227,305
43 000	340,560	4.00	5	0.9085	309,399
			10	0.8315	283,176
53 000	419,760	5.00	5	0.8874	372,495
			10	0.7955	333,919

1. Thermal efficiency is assumed to be 33 per cent.

2. In-core residence time (T) of fuel is assumed as follows:
   33 000 MWd per tonne : 3 years for irradiation including refuelling and maintenance.
   43 000 MWd per tonne : 4 years.
   53 000 MWd per tonne : 5 years.

3. Discount factor is calculated as follows:

$$\frac{1-\exp(-r' \times T)}{r' \times T}$$; where $r' = -\ell n(1 + r)$ and r = discount rate

Reload costs are shown in terms of cost per annum and per kWh at a discount rate of 5 per cent.

7. Effects of Plutonium Decay

Because plutonium decays during the storage of spent UO_2 fuel, its energy worth in thermal reactors decreases.

In order to attain the same burnup, more plutonium is required for MOX fuel using plutonium from 10 year stored spent fuel than from 4-year stored spent fuel.

This results in an increase in costs of reprocessing and waste disposal, because of the increase in the amount of spent fuel that has to be reprocessed (see Table H.3) to produce the desired plutonium.

Appendix H1 - THE EQUIVALENCE OF PLUTONIUM PRICING AND CREDITS

The idea that plutonium for MOX fuel manufacture should be priced on the basis of the costs of its recovery is raised in the main text, Section 2.6.2.2. It is not immediately obvious that the price differential between such MOX fuel and fresh uranium fuel is zero when the overall costs of once-through uranium fuel equal those of uranium fuel incurring reprocessing and fission product waste disposal costs but with credits allowed for recovered uranium and plutonium.

Their equivalence is demonstrated in the following calculation:

36 g of Pu_f are required to produce 1 kg HM of MOX fuel designed for 33 000 MWd per tonne burn-up. To produce this 36 g Pu_f 5.4 kg HM of spent 33 000 MWd per tonne uranium oxide fuel has to be reprocessed after taking recovery efficiencies into account (Annex H, Tables H.3 and H.7 derived from Tables 9 and 12 in main text).

Based on the simplified scheme in Figure H.1 of Annex H (and including for simplicity conversion costs as part of the uranium price (a), the costs of 1 kg of MOX fuel can be expressed as:

$$5.4ej^4 - 5.4gj^2 - 5.4dj^4 + hj^{0.5}$$

where j is the discount (compounding) factor and the lead times are taken from Table H.1. (Note reprocessing costs including waste conditioning and disposal, e is the discounted present value of reprocessing costs including waste conditioning and disposal, d is the discounted present value of spent fuel storage, conditioning and disposal. Both are discounted to a date 2 years prior to reprocessing and 4 years prior to recycle of recovered plutonium. Uranium credit g is valued at the time of recovery, i.e. 2 years later than spent fuel goes to the reprocessing plant).

For break-even this cost has to equal that of 1 kg HM of fresh 33 000 MWd per tonne uranium fuel; viz $aj^2 + bj + cj^{0.5}$ (assuming the back- end costs for the UO_2 and MOX cycles are the same, i.e. d=i).

Thus for MOX fuel use to be economically attractive:

$$aj^2 + bj + cj^{0.5} > 5.4ej^4 - 5.4gj^2 - 5.4dj^4 + hj^{0.5}$$

or $$aj^2 + bj + (c-h)j^{0.5} > 5.4j^4 (e-d-gj^{-2}) \qquad (a)$$

The economic attractiveness of reprocessing on the other hand depends on the comparative costs of once-through fuel and the costs of the reprocessing cycle as defined in the earlier study (4). Their respective costs using the appropriate discount factors are:

once-through: $aj^2 + bj + cj^{0.5} + dj^{-5}$

reprocessing: $aj^2 + bj + cj^{0.5} + ej^{-5} - fj^{-7} - gj^{-7}$

(credits f and g are obtained two years after spent fuel goes to the reprocessing plant due to the initial storage period. Fuel spends 3 years in the reactor and 2 years in the reactor pond after use).

Reprocessing is economic when:

$$dj^{-5} > ej^{-5} - fj^{-7} - gj^{-7}$$

or $$f > (e-d-gj^{-2})j^2 \qquad (b)$$

However f is itself derived from front-end equivalence costs (Section I.4) where:

$$f'j^{0.5} = \frac{1}{5.4}(aj^2 + bj + cj^{0.5} - hj^{0.5})$$

with f' credited 6 months before MOX fuel loading and 18 months after plutonium recovery

i.e. $$f = f'j^{-1.5}$$

Hence, substituting for f in (b)

$$j^{-2}(aj^2 + bj + cj^{0.5} - hj^{0.5})/5.4 > (e-d-gj^{-2})\,j^2$$

which rearranges to:

$$aj^2 + bj + (c-h)\,j^{0.5} > 5.4j^4\,(e-d-gj^{-2}) \qquad (c)$$

This is identical to equation (a) so that the criterion for reprocessing to be economic is identical to that for MOX fuel paying for plutonium recovery to be economic.

Thus the simple formulation derived from (b), above

$$f + g > (e-d)j^2$$

is a convenient indication of the economic attractiveness of recovering plutonium specifically for thermal recycle, where plutonium bears the costs of its recovery. f and g are the credits for plutonium and uranium per kg HM of spent uranium oxide fuel at the time of recovery (i.e., 4 years after removal of spent fuel from the reactor) and e and d the discounted present worth costs of reprocessing (including waste conditioning and disposal) and spent fuel storage, conditioning and disposal at 2 years after spent fuel is removed from the reactor (2 years before reprocessing).

The j^2 term arises from the 2 year interval between removing fuel from the at reactor store and the recovery of plutonium and uranium.

Annex I

GLOSSARY OF TERMS - ENGLISH/FRENCH DICTIONARY

Alpha-(α) particle [Particule alpha (α)]
A helium-4 nucleus emitted during a nuclear transformation; by extension, any helium-4 nucleus.

Activity (Activité)
The number of spontaneous nuclear disintegrations occurring in a given quantity of material per unit of time. It is commonly expressed in curies. (Also called disintegration rate).

Americium (Américium)
The plutonium-241 isotope decays into americium-241, a radioactive actinide emitting β-particles and γ-rays. Americium-241 is a neutron absorber (neutron poison).

ATR
Japanese Advanced Thermal Reactor.

Away-from-reactor Storage (Stockage en dehors du site du réacteur)
All storage facilities not integrated within a reactor facility, e.g. independent spent fuel storage installations, storage facilities at reprocessing plants or fuel cycle centres, storage facilities at disposal site.

Beta-(β) particle [Particule-bêta (β)]
An electron, of either positive or negative charge, which has been emitted by an atomic nucleus or neutron in a nuclear transformation.

Back-End [of the Fuel Cycle] [Partie terminale (ou aval) du cycle du combustible]
Those nuclear fuel cycle processes and activities concerned with the treatment of spent fuel discharged from reactors.

Breeding gain (Gain de surgénération)
Breeding ratio minus 1.

Breeding ratio (Rapport de surgénération)
The conversion ratio when it is greater than unity. A high breeding ratio results in a short doubling time.

Breeder reactor (Réacteur surgénérateur)
A nuclear reactor that produces more fissile material than it consumes. In fast breeder reactors, high-energy (fast) neutrons produce most of the fissions, while in thermal breeder reactors, fissions are principally caused by low-energy (thermal) neutrons. See Fast reactor.

Buffer storage (Stockage tampon)
Intermediate storage before reprocessing.

Burnable poison (Poison consommable)
Neutron absorbing material purposely included in a reactor to help control long-term reactivity changes by its progressive burn-up. (See also: burnable absorber).

Burnable absorber (Absorbant consommable)
Neutron absorber in a reactor that is consumed by neutron absorption in the course of the operation. In this way the decrease in reactivity, due to fuel burnup, is partly compensated. (See also: burnable poison).

Burn-up, specific (Taux de combustion ou combustion massique)
The total energy released per unit mass of a nuclear fuel; it is commonly expressed in megawatt-days per tonne.

CANDU [CANadian Deuterium Uranium reactor]
A type of heavy water reactor.

Cladding (Gaine)
An external layer of material applied directly to nuclear fuel or other material that provides protection from a chemically reactive environment and containment of radioactive products produced during the irradiation of the composite. It may also provide structural support.

Control rod (Barre de commande)
A control member in the form of a rod used to control the neutron flux in a nuclear reactor.

Conversion, chemical (Conversion chimique)
The operation of altering the chemical form of a nuclear material to a form suitable for its end use.

Conversion [in reactor technology] (Conversion ou régénération)
Nuclear transformation of a fertile substance into a fissile substance.

Conversion ratio (Rapport de conversion ou rapport de régénération)
The ratio of the number of fissile nuclei produced by conversion to the number of fissile nuclei destroyed. If the ratio for a given reactor is greater than one, it is a breeder reactor; if it is less than one, it is a converter reactor.

Converter reactor (Réacteur convertisseur)
A reactor that produces some fissile material, but less than it consumes.

Coolant (Fluide caloporteur, ou fluide de refroidissement)
The medium in a nuclear reactor which absorbs heat from the reactor core where fission occurs and heat is produced, and transfers it to systems which convert the heat into steam.

Cross section (section efficace)
A measure of the probability of a nuclear reaction occurring.

Cross section, capture (Section efficace de capture)
The cross section for capture, e.g. neutron capture.

Cross section, fission (Section efficace de fission)
The cross section for fission.

Depleted material (Matière appauvrie)

Material which has undergone depletion, i.e. reduction of the concentration of one or more specified isotopes. Depleted uranium is depleted in uranium-235.

Diffusion theory (Théorie de la diffusion)

An approximate theory for the diffusion of particles, especially neutrons, based on the assumption that in a homogeneous medium the current density is proportional to the gradient of the particle flux density.

Dose (Dose)

A general term denoting the quantity of radiation of energy absorbed. For special purposes, it must be appropriately qualified.

Doubling time as used in breeder reactor technology (Temps de doublement)

In its simplest form, the doubling time is defined as the time required for a breeder reactor to produce a surplus amount of fissile material equal to that required for the initial charge of the reactor. There are three types of doubling time:

i) *apparent linear doubling time*, which assumes that the reactor is never refuelled and none of the new fissile material is ever removed;
ii) *apparent compound doubling time* assumes that new fissile material is removed as soon as it is produced and placed in other breeders to produce more fissile material - the time to double the total amount of fissile material is apparent compound doubling time;
iii) *compound doubling time* includes "out of reactor" procedures such as the time required for refuelling the reactor reprocessing spent fuel rods, and refabricating new fuel rods; therefore it is the total time required for the amount of fuel material at any point in the reactor-reprocessing-refabrication chain to double.

Energy spectrum (Spectre d'énergie)

The energy distribution of particles or radiation.

Enriched material (Matière enrichie)

Material in which the concentration of one or more specified isotopes of a constituent is greater than its natural value.

Enrichment plant (Usine d'enrichissement)

A plant designed to enrich a specified isotope in an element by depleting it in the tailings.

Enrichment (Enrichissement)

i) the fraction of atoms of a specified isotope in a mixture of isotopes of the same element when this fraction exceeds that in the naturally occurring mixture;
ii) any process by which the content of a specified isotope in an element is increased.

Fabrication (Fabrication)

The process of preparing nuclear fuel pellets, and cladding them to make fuel elements and the incorporation of elements into assemblies ready for the reactor.

Fast (neutron) reactor (Réacteur à neutrons rapides ou réacteur rapide)

A nuclear reactor in which nearly all the neutrons liberated in fission have high energies and so, if no moderator is present in the reactor core or reflector, the majority of fissions are produced by fast neutrons. If a fertile species is present in the fast reactor core or in the blanket surrounding the core, it will be converted into fissile material by neutron capture. When the fissile nuclide produced is identical with that used to maintain the fission chain, the reactor is called a breeder.

Fertile material (Matière fertile)

A material, not itself fissionable by slow neutrons, that can be converted into a fissile material by irradiation in a reactor (by neutron capture, i.e. by the addition of a neutron to its nucleus). There are two basic fertile materials, uranium-238 and thorium-232. When these materials capture neutrons, they are partially converted into fissile plutonium-239 and uranium-233 respectively.

Fissile (Fissile)

i) of a nuclide, capable of undergoing fission by interaction with slow neutrons;
ii) of a material, containing one or more fissile nuclides.

Fission (Fission)

The physical process whereby the nucleus of a heavy atom is split into two (or, rarely, more) nuclei with masses of equal order of magnitude whose total mass is less than that of the original nucleus. The lost mass becomes energy according to Einstein's equation ($E = m_0c^2$). Fission is initiated by the capture of a neutron by the nucleus of a fissionable atom, and is accompanied by the emission of between one and three other neutrons (plus gamma radiation, and, rarely, smaller charged nuclear fragments). These neutrons in turn can fission adjacent nuclei, producing a self-perpetuating reaction, or chain reaction.

Fissionable (Fissionnable)

i) of a nuclide, capable of undergoing fission by any process;
ii) of a material, containing one or more fissionable nuclides.

Fission products (Produits de fission)

Nuclides produced either by fission or by the subsequent radioactive decay of the nuclides thus formed.

Flux density, particle [Fluence (de particules)]

At a given point in space, the number of particles incident per unit time on a suitably small sphere centred at that point divided by the cross-sectional area of that sphere. It is identical with the product of the particle density and the average speed.
Note: this quantity may also be referred to as particle fluence rate. It is also commonly, but incorrectly, called flux.

Fuel, nuclear (Combustible nucléaire)

Material containing fissile nuclides which, when placed in a reactor, enables a self-sustaining nuclear chain to be achieved.

Fuel assembly (Assemblage combustible)

A grouping of fuel elements which is not taken apart during the charging and discharging of the reactor core.

Fuel cycle (Cycle du combustible)

The sequence of processing, manufacturing, and transportation steps involved in producing fuel for a nuclear reactor, and in processing fuel discharged from the reactor. The uranium fuel cycle includes uranium mining and milling, conversion to uranium hexafluoride (UF_6), isotopic enrichment, fuel fabrication, reprocessing, recycling to recovered fissile isotopes, and disposal of radioactive wastes.

Fuel element (Elément combustible)

The smallest structurally discrete part of a reactor which has fuel as its principal constituent. Special forms of fuel element are: fuel pin, fuel plate and fuel rod.

Fuel pin (Aiguille de combustible)
A fuel element in the form of a pin. (See: fuel element).

Fuel rod [Barre (cartouche) de combustible]
A fuel element in the form of a rod. (See: fuel element).

Fusion reactor (Réacteur à fusion)
A reactor relying on the fusion or joining of the nuclei of light elements to produce its energy.

Gain (Gain)
See breeding gain.

Gamma-(γ) radiation [Rayonnement-gamma (γ)]
Electromagnetic radiation emitted in the process of nuclear transformation or particle annihilation.

Gas-centrifuge process (Procédé par centrifugation gazeuse)
A method of isotopic separation in which heavy gaseous atoms or molecules are separated from light atoms or molecules by centrifugal force.

Gas-Graphite Reactor (Réacteur gaz-graphite)
A graphite-moderated, carbon dioxide (CO_2)-cooled reactor.

Glove box (Boite à gants)
An air-tight enclosure fitted with gloves for visible handling of poisonous or radioactive materials.

GWe (gigawatt électrique)
Gigawatt (10^9 watts) electric.

Half-life, radioactive (Période radioactive)
For a single radioactive decay process, the time required for the activity to decrease to half its value by that process.

H.M. (ML ou métal lourd)
Heavy metal, that means all the isotopes of Th, U, Np, Pu, Am and Cm.

Heavy water (Eau lourde)
Deuterium protoxide (D_2O): water containing significantly more than the natural proportion (1 in 6500) of heavy hydrogen (deuterium) atoms to ordinary hydrogen atoms.

Heavy-Water Reactor (Réacteur à eau lourde)
Heavy water is used as a moderator in certain reactors because it slows down neutrons effectively and also has a low cross section for absorption of neutrons.

Indifference value [of plutonium] (Valeur d'indifférence du plutonium)
This is the value that plutonium would have in order to produce MOX fuel and equivalent uranium oxide fuel at equal cost.

Initial core (Premier coeur)
Core containing the first fuel charge of a reactor.

Irradiation (Irradiation)
Exposure to ionizing radiation.

Irradiated fuel (Combustible irradié)
Fuel that has undergone nuclear transformation of its constituent atoms during reactor operation.

Isotopes (Isotopes ou nucléides isotopes)
Nuclides having the same atomic number (i.e. identical chemical element) but different mass numbers; e.g. uranium-235 and uranium-238 nuclei contain the same number of protons (92) which determine atomic number, but different numbers of neutrons (143 and 146 respectively). Isotopes have the same chemical properties but slightly different physical properties.

KWh
Kilowatthour (10^3 watthour).

Load factor (Facteur de charge)
The load factor of a nuclear unit or station for a given period of time is the ratio of the energy that is produced during the period relative to the energy that it could have produced at maximum capacity under continuous operation during the whole of that period. Also called Capacity Factor.

Load following (Suivi de charge)
The requirement for a nuclear reactor or other power plant to vary its output to keep pace with load variations.

Light Water Reactor (Réacteur à eau ordinaire)
A nuclear reactor that uses ordinary water as both a moderator and a coolant and utilises slightly enriched uranium-235 fuel. There are two commercial LWR types: the boiling-water reactor (BWR) and the pressurized water reactor (PWR).

Magnox (Magnox)
A magnesium alloy with low aluminium content, used as a cladding material in certain reactors (magnox reactors).

Mixed Oxide or MOX (Oxydes Mixtes U-PuO2)
A mixture of plutonium dioxide and uranium dioxide.

Moderator (Modérateur, ou ralentisseur)
A material, such as ordinary water, heavy water, or graphite, used in a nuclear reactor to slow down high-velocity neutrons so fissile nuclei can more easily and efficiently capture them, thus increasing the likelihood of further fission.

MOX fuel element (Elément combustible MOX)
Mixed Oxide fuel element: fuel element in which fuel is an intimate mixture of uranium and plutonium oxides.

MWe (Mégawatt électrique)
Megawatt (10^6 watts) electric.

MWh
Megawatthour (10^6 watthour).

Neptunium (Neptunium)
A heavy, man-made metallic element with atomic number 93, created by absorption of neutrons in uranium-238. It rapidly decays to plutonium-238 by electron emission.

Neutron (Neutron)
An elementary particle having no electric charge, a rest mass of 1.67482 x 10^{-27} kg, and a mean life of 1000 s.

Neutron density (densité de neutrons)
The number of neutrons per unit volume, e.g., cm^3.

Neutron flux (Débit de fluence neutronique)
The neutron flux Ø is the product of the neutron density n and velocity v:

Ø = nv , i.e. neutrons per cm^3 per second

Neutrons, fast (Neutrons rapides)
Neutrons of kinetic energy greater than some specified value. This value may vary over a wide range and will be dependent upon the application, such as reactor physics, shielding, or dosimetry. In reactor physics the value is frequently chosen to be 100 000 eV (electron-Volt).

Neutrons, slow (Neutrons lents)
Neutrons of kinetic energy less than some specified value (see neutrons, fast). In reactor physics, the value is frequently chosen to be 1 eV.

Neutrons, thermal (Neutrons thermiques)
Neutrons in thermal equilibrium with the medium in which they exist.

Neutron spectrum (Spectre de neutrons)
The energy distribution of neutrons in a reactor.

Nuclear energy (Energie nucléaire)
Energy released in nuclear reactions or transitions.

Nuclear fuel (Combustible nucléaire)
See Fuel, nuclear.

Nuclear power plant (Centrale nucléaire)
A reactor or reactors together with all structures, systems and components necessary for the production of power (i.e. heat or electricity).

Nucleus (Noyau)
The positively charged central portion of an atom with which is associated almost the whole mass of the atom, but only a minute part of its volume.

Nuclide (Nucléide)
A species of atom characterized by its mass number, atomic number, and nuclear energy state, provided that the mean life in that state is long enough to be observable.

Once-through mode (Cycle à passage unique)
Fuel cycle in which fuel goes only through the reactor once; no spent fuel reprocessing is foreseen.

Optimum tails composition (Composition optimale des rejets)
The composition or assay of enrichment tailings which leads to the lowest cost of enriched uranium. Its calculation is based on:

- prices for natural uranium
- price for conversion
- price for enrichment
- conversion loss of 0.5 per cent

Out-of-pile time (Temps de séjour hors réacteur)
Time required from the date of spent fuel discharge to the date at which plutonium from that spent fuel can be loaded into the reactor.

Pin [fuel element] (Aiguille de combustible)
See: fuel element.

Plutonium (Plutonium)
A heavy, radioactive, metallic element with atomic number 94, created by absorption of neutrons in uranium-238. Its most important isotope is plutonium-239, which is fissile.

Plutonium credit (Crédit plutonium)
The value of plutonium in irradiated uranium. This term usually refers to plutonium formed by conversion in thermal reactors, as opposed to breeding in fast reactors.

Plutonium equivalent worth [Pu(E)] (Valeur equivalente en plutonium)
Equivalent mass of Pu-239 with the same fission-neutron yield characteristics as a specific sample.

Poison, nuclear (Poison nucléaire)
A substance which, because of its high neutron absorption cross section, reduces reactivity.

Positron (Positron)
A positively charged electron (the antiparticle to the electron).

Pressurized Water Reactor [PWR] (Réacteur à eau sous pression [REP])
A light water moderated and cooled reactor that employs an indirect cycle; the cooling water that passes through the reactor is kept under high pressure to keep it from boiling, but it heats water in a secondary loop that produces steam that drives the turbine.

Radioactive waste (Déchets radioactifs)
The unwanted radioactive materials formed by fission and other nuclear processes in a reactor or obtained in the processing or handling of radioactive materials. Most nuclear waste is initially in the form of spent fuel. If this material is reprocessed, new categories of waste result: high-level, transuranic, and low-level wastes (as well as others).

Radioactive waste disposal [Stockage définitif (ou évacuation) des déchets radioactifs]
The disposition of radioactive waste in repositories, after appropriate conditioning, without specific provision for recovery.

Radiotoxicity (Radiotoxicité)
Characteristic of certain radioactive substances that result in hazard to man when ingested or inhaled.

Reactivity (Réactivité)

A parameter, p, giving the deviation from criticality of a nuclear chain-reacting medium such that positive values correspond to a supercritical state and negative values to a subcritical state.

Quantitatively:

$$p = 1 - \frac{1}{K_{eff}}$$

where K_{eff} is the effective multiplication factor.

Repository, waste (Dépôt de déchets radioactifs)

See: waste repository.

Reprocessing, spent fuel (Retraitement du combustible irradié)

A generic term for the chemical and mechanical processes applied to fuel elements discharged from a nuclear reactor whose purpose is to remove fission products and recover fissile (uranium-233, uranium-235, plutonium-239), fertile (thorium-232, uranium-238) and other valuable material.

Safeguards (Garanties)

Term used to refer to the total set of international verifications, observations, etc., which together constitute a determination that nuclear materials (or, in some international agreements, facilities or other materials) have not been diverted from the nuclear power programme to which they have been assigned.

Separative Work (Travail de séparation isotopique)

This quantity is linked to the minimum energy required to separate a given amount of material of isotopic abundance X in two parts of isotopic abundances Y and Z (isotopic abundance is the relative number of atoms of a particular isotope in a mixture of the isotopes of an element, expressed as a fraction of all the atoms of the element).

Separative Work Units [SWU] (Unités de Travail de Séparation Isotopique [UTS])

The Separative Work Unit has the dimension of a mass; the SWU can be expressed in kilograms.

Shut down (Arrêt [d'un réacteur])

The procedure of making a reactor substantially subcritical. Also, the state of a reactor in a substantially subcritical condition.

Solvent extraction in fuel reprocessing (Extraction par solvant)

A process in which a substance is selectively extracted from an aqueous medium by means of an immiscible organic solvent.

Note - Sometimes this term is generalised to mean *extraction cycle.*

Speculative Resources [SR] (Ressources Spéculatives [RS])

Refers to uranium, in addition to Estimated Additional Resources - Category II, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative.

Spent fuel (Combustible irradié ou usé ou épuisé)

Nuclear fuel removed from a reactor following irradiation.

Spent fuel disposal (Evacuation du combustible irradié)
Permanent disposal of spent fuel (after conditioning) without reprocessing.

Spent fuel storage, long-term or indefinite (Stockage à long terme ou illimité du combustible irradié)
Storage of spent fuel elements in a retrievable form for a period exceeding two decades.

Spot market (Marché spot)
The market for short term uranium contracts, served by broker companies such as NUEXCO and NUKEM.

Storage (stockage)
See spent fuel storage.

Surface dose rate (Débit de dose surfacique)
Flux of radiation (X-rays, gamma-rays, alpha-rays, neutrons) at the surface of a sphere of radioactive material.

SWU (UTS ou Unité de Travail de Séparation Isotopique)
See Separative Work Unit.

Tailings (Rejets ou résidus)
Waste material from a separation process. Commonly the finely divided waste from a mineral separation operation but also used to describe depleted uranium from an enrichment plant.

Thermal efficiency (Rendement thermique)
The proportion of heat energy produced in a power plant that is converted to gross electrical output.

Thermal reactor (Réacteur thermique)
A reactor in which fission is induced predominantly by thermal neutrons.

Thorium (Thorium)
A radioactive element of atomic number 90; naturally occurring thorium has one main isotope - thorium-232. The absorption of a neutron by a thorium atom can result in the creation of the fissile material uranium-233.

Transport theory [reactor technology] (Théorie du transport [technologie des réacteurs])
A theory for the treatment of neutron or gamma-ray migration in a medium based on the linear Boltzman transport equation.

Transuramic elements (Transuraniens)
Elements having higher atomic numbers (nuclear charges) than uranium, e.g. neptunium, plutonium, curium.

TWh
Terawatt (10^{12} watt) hours.

Uranium (Uranium)
A radioactive element of atomic number 92. Naturally occurring uranium is a mixture of 99.28 per cent uranium-238, 0.715 per cent uranium-235, and 0.0058 per cent uranium-234. Uranium-235 is a fissile material and is the primary fuel of nuclear reactors. When bombarded with slow or fast neutrons, it will undergo fission. Uranium-238 is a fertile material that is transmuted to plutonium-239 upon the absorption of a neutron.

Waste conditioning (Conditionnement des déchets radioactifs)
The preparation of radioactive waste for disposal.

Waste disposal (Stockage définitif ou évacuation des déchets radioactifs)
See: Radioactive waste disposal.

Waste repository (Dépôt de déchets radioactifs)
Prepared geological site suitable for permanent disposal of radioactive waste.

Waste storage (Stockage des déchets radioactifs)
The storage of radioactive waste in a special facility, in such a way that it remains retrievable.

WOCA (MEM ou Monde à Economie de Marché)
World Outside CPE Areas.

X radiation (Rayonnement X)
Penetrating electromagnetic radiation other than annihilation radiation originating in the extra-nuclear part of the atom and having wave lengths much shorter than those of visible light.

Note - The term most often applies to the bremsstrahlung of electrons being retarded by the Coulomb field of atoms in a target material (X-ray continuum) and to the radiation of discrete energy accompanying the transitions of orbital atomic electrons to levels of lower potential energy (characteristic X-rays).

Annex J

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