Journal of the Korean Nuclear Society
Volume 12, *Number* 3, *September*, 1980

《**Review**》

The ROK Nuclear Power Programme —Some Aspects of Radioactive Waste Management in the Nuclear Fuel Cycle—

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(Received May 23, 1980)

Abstract

The paper describes and quantifies the wastes arising in the nuclear fuel cycle for Light Water Reactors, Heavy Water Reactors and Fast Breeder Reactors. The management and disposal technologies are indicated, together with their environmental impacts. Both once-through and uranium-plutonium recycle systems are evaluated, and comparisons are made on the basis of single reference technologies for waste management, and for one gigawatt/year of electricity generation. Environmental impacts are assessed, particularly that of health and safety, and a reference costing system is applied purely as a basis for comparing the fuel cycles.

From this study it can be concluded generally that the relative differences of the impacts of waste management and disposal between the selected fuel cycles are not decisive factors in choosing a fuel cycle. Employing the technologies assumed, the radioactive wastes from any of the fuel cycles studied can be managed and disposed of with a high degree of safety and without undue risk to man or the environment. The cost of waste management and disposal is only a few percent of the value of the electricity generated and does not vary greatly between fuel cycles.

1. Introduction

I understand that, in order to meet the energy demand of your Country's economic growth, you have already planned to have 13 units of nuclear power production in operation by the year 1991, and that some projections have already been made for a further 18 units by the year 2000, providing a total of 29.5 GW of electricity generating capacity. At the present time you have one unit in operation with at least 7 other units at some stage of construction or design. By any standards this is a major and most challenging project.

Since my presence here at this institute is related to radioactive waste management matters, I feel that it would be of interest to you to consider some of the radioactive waste management and disposal aspects arising from such a major nuclear power programme.

Clearly in the short time available for the

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preparation of this paper it has not been possible to carry out all the calculations and assessments for such an overall study. Reference is therefore made to the work carried out during the recent International Nuclear Fuel Cycle Evaluation at which I was a United kingdom delegate to Working Group 6 and Working Group 7.

In that study a constant level of power production was assumed, based on a single fuel cycle, over an indefinite length of time and without technological change. Furthermore it was assumed that there was no coupling between the fuel cycle under consideration and other fuel cycles, and that all materials produced within the fuel cycle are waste, unless they can be re-used within the same fuel cycle.

This definition of wastes is somewhat artificial not only because what is waste in one fuel cycle could be a useful raw material in another, but also because some of the materials could be applied for other purposes than the generation of electricity. One example of this is the use of depleted uranium as a high density metal. Another is the use of cobalt, which has been used as a neutron absorber for reactivity control, as a gamma radiation source for industrial and for medical purposes.

2. Nuclear fuel Cycle Options

Basically three types of reactor are under consideration in your nuclear power programme, Light Water Reactors, Heavy Water Reactors, and the Fast Breeder Reactor. In each of the first two of these there is the option of once-through operation, or uranium-plutonium recycle, thus making a total of five nuclear fuel cycle options:

1) L.W.R. once-through
2) L.W.R. U-Pu cycle
3) H.W.R. once-through
4) H.W.R. U-Pu cycle
5) F.B.R.

It may be useful to consider the key fuel cycle parameters affecting waste management and disposal. Their values are summarized in Table 1. With regard to the figures for heavy metal in this table, it is interesting to note that the generation of electricity from coal can also be characterised by similar values per GWa (Gigawatt year) of electricity. Thus for typical uranium concentrations in coal of 1 to 100 ppm the figures for heavy metal would range from 3 to 300. In this case the uranium and its daughter nuclides are dispersed with the fly-ash or are dumped with the bottom ash.

Table 1. Principal Characteristics of the Fuel Cycles.

Fuel cycle	Heavy metal extracted from ore per GWa electric (P), Metric Tonne	Quantity of fission products produced, Metric Tonne	Effective mass number range in fresh fuel*
LWR once-through	205.4	3.08	235−238
LWR U-Pu cycle	119.5	3.08	235−239
HWR once-through	178.8	3.41	235−238
HWR U-Pu cycle	74.6	3.41	235−239
FBR	1.2	2.74	238−240

* Smallest and largest mass number of nuclei in fresh fuel with concentrations exceeding 0.70%

The factors determining the quantities of the transuranium nuclides, some of which are responsible for the long term hazards of radioactive waste, are more complex. Since these nuclides are formed by multiple neutron capture in lighter nuclides, a relevant parameter, listed in Table 1, is the mass range of the nuclides in the fuel.

Heavy element flow-sheets per GWa of electricity for the five selected fuel cycles are given in Figures 1-5. Reference is made in these flow-sheets to the ^{235}U content of the heavy metal in terms of percentage and also to the plutonium that is produced. With regard to waste management it is interesting to note the varied quantities of plutonium arising in the wastes from the different fuel cycles.

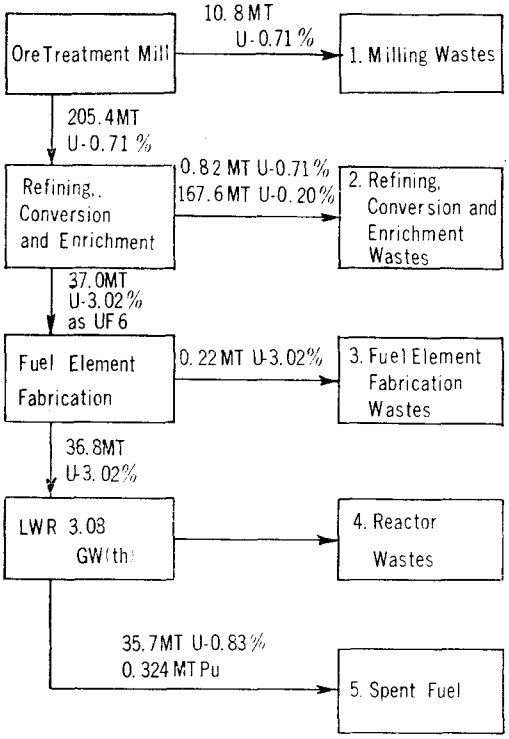

Fig. 1. LWR Once-Through. Heavy Element Flow Sheet Per GW Year of Electricity

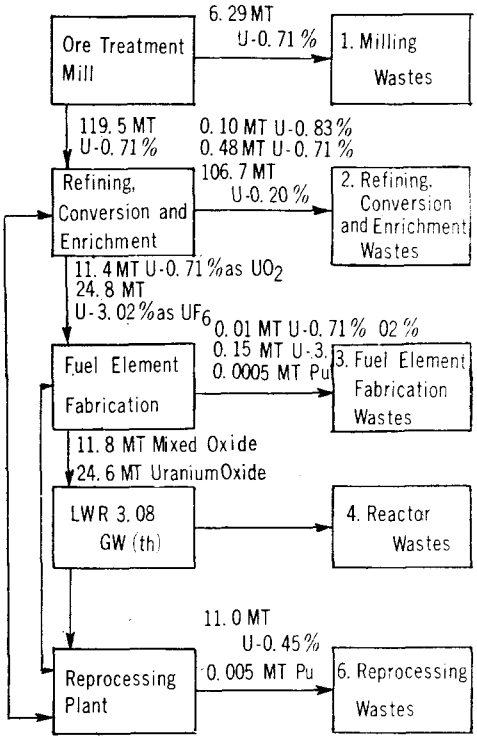

Fig. 2. LWR with U-Pu Cycle. Heavy Element Flow Sheet Per GW Year of Electricity

3. Waste Arisings, Conditioning and Transport

In the fuel cycle flow sheets shown in Figures 1-5 the waste products have been grouped as follows:

1) Waste from uranium ore processing
2) Refining, conversion and enrichement wastes
3) Fuel element fabrication wastes
4) Reactor wastes
5) Un-reprocessed spent fuel
6) Reprocessing wastes

The same headings are used in estimating the quantities of waste products for 1 GWa of electricity produced in each of the five selected fuel cycles, in a form which allows them to be conveyed to a waste repository. These quantities, which are summarized in Table 2. are needed for estimating the repository space required and for impact assessments in respect to health and safety. It is therefore first necessary to characterise

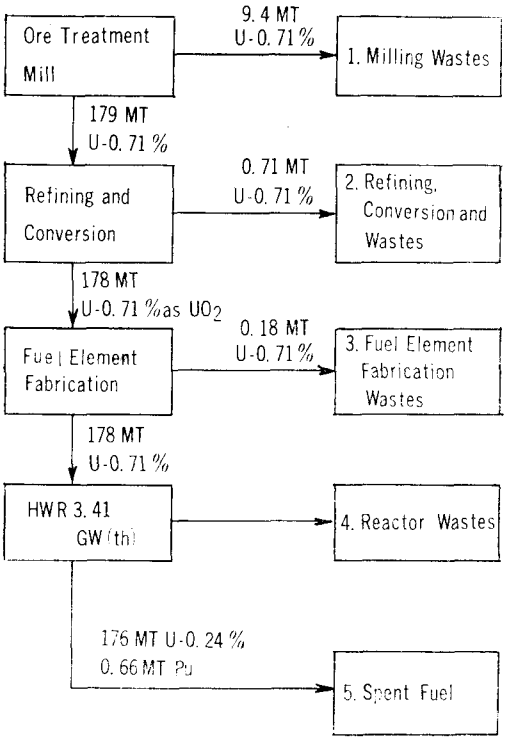

Fig. 3. HWR Once-Through. Heavy Element Flow Sheet Per GW Year of Electricity

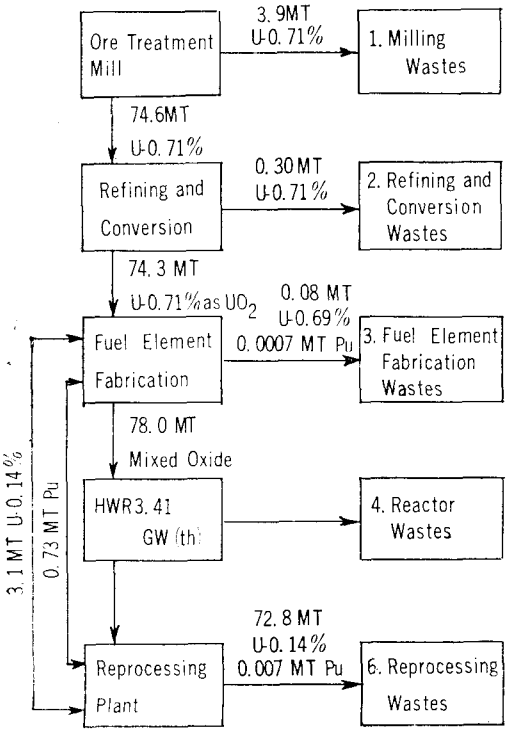

Fig. 4. HWR with U-Pu Cycle. Heavy Element Flow Sheet Per GW Year of Electricity

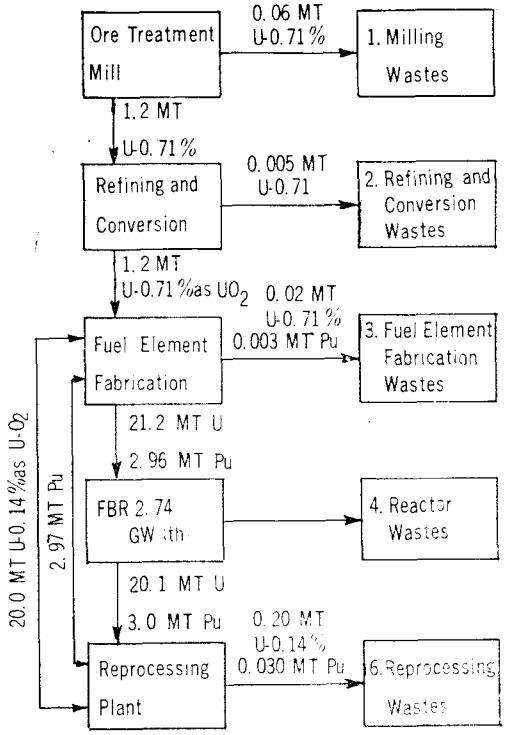

Fig. 5. FBR With U-Pu Cycle. Heavy Element Flow Sheet Per GW Year of Electricity

the primary waste products under each heading in kind and quantity, in particular their content of heavy elements, other radioactive nuclides, and any non-radioactive constituents relevant to waste management. Furthermore, for each kind of waste the conditioning method has to be specified not only to allow the quantities of conditioned waste products to be calculated, but also because these methods from part of the data base for impact assessments.

It is assumed that, with the exception of the mill tailings from ore processing, the conditioned waste products arise at a location different from that of the waste repository. Thus transport has to be considered.

3.1 Wastes from Uranium Ore Processing

All the selected fuel cycles have as a first waste producing step the extraction of

Table 2. Summary of Packaged Waste Arisings Per GWa of Electricity.

Waste origin	Ref. Table	Package type	LWR		HWR		FBR
			Once -through	U-Pu cycle	Once -through	U-Pu cycle	
Conversion and enrichment plant		Drum, unshielded	364	221	122	51	18
Fuel element fabrication plant		Drum, unshielded	200	285	498	750	318
Power plant		Drum, unshielded	1,800	1,800	1,547	1,547	15
		Drum, shielded	600	600	524	524	610
		Canister, HWR	3	10	—	—	7
Spent fuel conditioning plant		Drum, shielded	45	—	80	—	—
		Can ster, PWR	53	—	—	—	—
		Canister, BWR	22	—	—	—	—
		Canister, HWR	—	—	132	—	—
Fuel reprocessing plant		Drum, unshielded	—	320	—	747	201
		Drum, shielded	—	112	—	237	72
		Canister, HWR	—	33	—	31	86
		Canister, HLWs	—	29	—	29	23
		Canister, HLWg	—	67	—	67	53
		Gas flask	—	17	—	17	17
Total Packaged Waste		Drum, unshielded	2,364	2,626	2,167	3,095	552
		Drum, shielded	645	712	604	761	682
		Canister, PWR	53	—	—	—	—
		Canister, BWR	22	—	—	—	—
		Canister, HWR	3	43	132	31	93
		Canister, HLWs	—	29	—	29	23
		Canister, HLWg	—	67	—	67	53
		Gas flask	—	17	—	17	17

uranium from the ore. This involves the crushing and grinding of the rock, followed by leaching, usually with acid. The uranium is recovered from the leaching solution by liquid-liquid extraction and precipitated as ammonium diuranate (ADU).

The quantity of ore needed per GWa of electricity is determined by the required tonnage of natural uranium (see Table 1), the uranium content of the ore and the efficiency of uranium extraction. For this study a uranium content of 0.2% by weight and an extraction efficiency of 95% are assumed. With these figures one finds for the solid ore residue (mill tailings) a mass of 525P metric tonnes (P=natural uranium tonnage required, Table 1).

The mill tailings are a slurry of the ore residue in water containing some of the process chemicals. Despite the fact that the waste contains only natural constituents it requires careful management. This is because the mining and the acidification of the ore increase the possibility for these constituents to enter the biosphere.

The inherent radioactivity of the mill tailings is primarily due to the members of the ^{238}U decay chain. One MT of ^{238}U represents a radioactivity of 0.33Ci. Taking into account the assumed extraction efficiency it follows that the ^{238}U activity in the ore is 0.35P Ci per GWa. Assuming secular equilibrium to exist in the ore, this must also be the radioactivity of the decay pro-

ducts. Of these the following have half-lives exceeding one year:

^{234}U	250,000years
^{230}Th	80,000years
^{226}Ra	1,600years
^{210}Pb	22years

With the assumed extraction efficiency, 5% of the ^{234}U as well as the ^{238}U will be left in the tailings, representing radioactivites of 0.0175P Ci. It is assumed that 5% of the thorium is extracted with the uranium but that the other radionuclides remain 100% in the mill tailings. Among them ^{226}Ra is the most important with regard to health and safety, because of the hazard of it being ingested by aqueous pathways as well as through its gaseous daughter ^{222}Radon (half-life 3.8 days).

Due to the addition of process chemicals, including the neutralizing agent, the actual mass of the mill tailings is about 569P MT per GWa, or assuming a bulk density of the dry material of 2.0MT/m^3, a volume of 285 P.m^3. This expression and those derived earlier for the contained radioactivities have been used to compute the figures for milling wastes contained in Table 3.

3.2 Refining, Conversion and Enrichment Wastes.

The ammonium diuranate obtained from ore processing has first to be purified and converted to the proper feed material for the next fuel cycle step. For some of the fuel cycles this is uranium dioxide. In the other fuel cycles, all or part of the uranium has to be enriched, which entails conversion into uranium hexafluoride(UF_6). Both these chemical conversions produce waste, which

Table 3. Milling Wastes Per GWa of Electricity.

	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
Volume in m^3 containing radioactivity in Ci of	58540	34060	50960	21260	342
^{238}U, ^{234}U each	3.6	2.1	3.1	1.3	0.02
^{230}Th	68	40	60	25	2.4
^{226}Ra, ^{210}Pb each	72	42	63	26	2.6

Table 4. Refining, Conversion and Enrichment Wastes Per GWa of Electricity.

	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
1. Refining and conversion wastes					
Drums, unshielded	163	95	122	51	18
containing Uranium MT	0.8	0.6	0.7	0.3	0.01
^{234}Th Ci	3.6	2.1	3.1	1.3	0.02
2. Enrichment wastes					
Drums, unshielded	191	121	—	—	—
containing Uranium MT as UO_2	168	107	—	—	—
3. Enrichment plant maintenance waste					
Drums, unshielded	10	5	—	—	—
containing Uranium kg	40	20	—	—	—

is packaged in 200 litre steel drums. The numbers of these drums given in Table 4 are based on available industrial experience. They are assumed to contain 0.4% of the natural uranium handled as well as the ^{230}Th content of the ADU. The same percentage loss of uranium is assumed in the conversion of uranium dioxide from the reprocessing plant to hexafluoride for recycle. The major waste product in this category is UF_6 containing depleted uranium in the quantities shown in the heavy element flow sheets (Figures 1-5).

In addition to the drums needed for the conversion wastes, smaller numbers of drums have been listed in Table 4 for the maintenance and decommissioning waste of the enrichment plant, which contains insignificant quantities of uranium of varying isotopic composition.

3.3 Fuel Element Fabrication Wastes

The reactors considered in this study all have cores consisting of one or more types of assemblies containing fuel and/or fertile material as oxides. In the fuel fabrication plant these are made into the required shapes by blending, pressing and grinding. The only chemical operation envisaged in the fuel element plant is the conversion of UF_6 into UO_2. As a by-product this yields calcium fluoride contaminated by uranium. It is assumed that 0.5% of the material handled is lost in this way, and the losses in all other operations together have been set at 0.1%. All wastes from the fuel element fabrication plant are packaged in unshielded drums, but wastes containing plutonium are first mixed with concrete to improve immobilisation. The numbers of drums listed in Table 5 are derived from industrial experience.

3.4 Reactor Wastes

Due to the combined effects of neutron bombardment and corrosion, activation products of the reactor structural materials, as well as any fission products escaping from the fuel elements will enter the coolant circuits and eventually spread to other parts of the plant. Filters and ion-exchangers that have been used to trap this radioactivity form the main constituent of the reactor operation wastes (item 1 Table 6). The structural parts themselves are the principal source of maintenance wastes (Item 2 Table 6).

The radioactivities in Table 6 have been estimated on the assumption that the operating and maintenance wastes are packed and shipped once per year. The radioactivity figures for the LWR represent a consensus

Table 5. Fuel Element Fabrication Wastes Per GWa of Electricity.

Waste type and packaging	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
1. Uranium oxide fuel waste					
Drums, unshielded	200	130	498	—	—
containing Uranium Kg	220	150	180	—	—
2. Mixed oxide fuel waste					
Drums, unshielded	—	155	—	750	318
containing Uranium Kg	—	10	—	80	20
Plutonium Kg	—	0.5	—	0.7	3

Table 6. Reactor Wastes Per GWa of Electricity.

Type of waste	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
1. Operation wastes					
Drums, unshielded	1,800	1,800	1,539	1,539	15
Drums, shielded	200	200	373	373	15
Radioactivity KCi (1 year)	7	7	3	3	2
2. Maintenance wastes					
Drums, shielded	275	275	69	69	470
Radioactivity KCi (1 year)	0.1	0.1	2.3	2.3	0.1
3. Control rods, etc					
Canister HWR	3	10	—	—	7
Radioactivity KCi (1 year)	190	190	—	—	100
4. Decommissioning wastes					
Drums, unshielded	—	—	8	8	—
Drums, shielded	125	125	82	82	125
Radioactivity KCi (25 years)	3	3	16	16	3

of a number of countries. The HWR figures are based on the CANDU PHW generating system waste arisings. The numbers of drums, shielded and unshielded, in which the various wastes, if necessary immobilised and shielded in concrete, are assumed to be packaged were taken from the same sources.

For reactors with batchwise refuelling the principal type of operating waste in terms of radioactivity is formed by the absorber assemblies used for reactivity control. Therefore these are listed separately as item 3 in Table 6 for fuel cycles 1, 2 and 5. Since the absorber rods of a pressurised water reactor may be moved into the fuel elements, it is assumed that for once-through fuel cycle 1 they are placed in canisters with the spent fuel. In all other cases it is assumed that the absorber assemblies, after dissection, are packed in large diameter (86 cm) steel canisters (the HWR canister).

For estimating the decommissioning wastes (Item 4 of Table 6), it is conservatively assumed that after a life span of 30 years the reactor is entombed. This requires the removal, as waste, of all components that would remain a health hazard for longer than the expected life of the entombment structure. All radioactive components remaining inside the biological shield are sealed into the shield and the building is maintained as necessary to provide adequate shielding and containment. The figures in Table 4 are based on a load factor of 70% for the LWR and FBR cycles, and 80% for the HWR with on-load refuelling. For the HWR this waste item includes the absorber rods for reactivity control.

3.5. Unreprocessed Spent Fuel

For this study it is assumed that spent fuel elements to be treated as waste remain in the interim storage of the reactor for 10 years after reactor discharge, before being conditioned for emplacement in the geological repository. Two packaging methods have

been considered. The canisters are of two types, both cylindrical, one holding a single PWR fuel assembly and the other accommodating three BWR fuel assemblies. The numbers of canisters of each type appearing in Table 7 for the LWR once-through cycle are based on an assumed mix of PWRs and BWRs in the ratio of 2 : 1. The spent fuel bundles of the HWR are packed in a canister holding 72. Some radioactive waste remains as a by-product of the packaging of spent fuel assemblies. It is assumed that this waste is mixed with concrete and packed in shielded drums.

Table 7. Conditioned Unreprocessed Spent Fuel Per GWa of Electricity

Type of wasts	LWR	HWR
1. Conditioned fuel assemblies		
Canisters PWR	53	—
Canisters BWR	22	—
Canisters HWR	—	132
containing Uranium MT	35.7	126
Plutonium MT	0.32	0.66
radioactivity (10 years) MCi	13.2	14.4
2. Spent fuel conditioning waste*		
Drums, shielded	45	80
radioactivity (1 year) KCi	0.14	0.17

* Decommissioning waste is included.

3.6. Reprocessing Waste

For this waste a reference plant for reprocessing 1,000MT of LWR fuel per year, modified as necessary, is assumed to be used in the three fuel cycles with fuel reprocessing and U-Pu recycle.

The metal clad spent fuel assemblies and chopped and exposed to acid which dissolves most of the fuel. However, some of the radioactive fuel constituents have penetrated into or adhered to the cladding hulls, which are themselves radioactive. Together with other structural parts of the fuel assemblies and insoluble fuel residues they constitute item 1 of Table 8. In the dissolving process ^{85}Krypton and other gaseous fission products escape. These gases are assumed to be trapped and collected in steel flasks, forming item 3 of Table 8. The ^{129}Iodine also escapes and is trapped on a special filter which is included in item 5.

Liquid-liquid extraction of the fuel solution results in separate aqueous process streams containing uranium, plutonium and the fission products plus transplutonium elements respectively. The uranium and plutonium are recovered in solid form. Uranium which is not recycled gives rise to waste at item 4 of Table 8. The fission product solution is stored in steel tanks which are designed for removal of the decay heat. The radioactivities listed for this waste at item 2 of Table 8 are based on cooling for 10 years.

It is planned to convert the solutions of fission products and transplutonium elements into a solid by means of a vitrification process. The radioactive solution is dried and calcined, and glass frit is added to form a borosilicate glass which is poured into high-level waste (HLW) canisters. Two different canisters may be used, with capacities of 0.177 and 0.077m^3 respectively, depending on whether the storage repository is in salt or hard rock, the composition of the glass being equal. After filling, the HLW canisters are closed by welding and then decontaminated.

The concentration of radioactive waste and other components in the borosilicate glass can be adjusted to yield a glass with the desired chemical and physical properties. For this study the volume of glass resulting from the reprocessing of 1 MT of LWR fuel is taken to be 0.15m^3. The values in Table 8 for the other fuel cycles assume an

Table 8. Reprocessing Waste Per GWa of Electricity

Waste type and packaging	LWR	HWR	FBR
1. Hulls, spacers, insolubles			
Canister HWR	33	31	86
contained plutonium, Kg	1.4	2.1	9.0
radioactivity (1 year), MCi	1.4	0.5	1.6
2. Vitrified high level waste			
Canister HLWs	29	29	23
Canister HLWg	67	67	53
contained plutonium, Kg	2.3	3.6	15.1
radioactivity (10 years) MCi	11.7	12.2	7.8
3. Gas flasks	17	17	17
radioactivity, MCi	0.3	0.3	0.2
4. Depleted uranium waste			
Drums, unshielded	13	83	1
contained uranium, MT	11	73	0.2
5. Medium level & Plant maintenance			
Drums, unshielded	54	118	35
Drums, shielded	83	177	54
contained plutonium, Kg	0.9	1.5	5.9
radioactivity (1 year), KCi	2.0	4.0	1.5
6. Low level waste			
Drums, unshielded	113	244	74
Drums, shielded	13	27	8
radioactivity (1 year), KCi	4	8	2.4
7. Plant decommissioning waste			
Drums, unshielded	140	302	91
Drums, shielded	16	33	10
radioactivity (5 years), KCi	0.9	2	0.6

equal mass concentration of fission products in the glass.

Next in radioactivity after the vitrified waste are the chopped hulls and other parts of the fuel assemblies. It is assumed that these together with residues are suitably immobilised in HWR type canisters. The numbers shown are derived from values given for the reference plant.

The gaseous fission products krypton and xenon collected during dissolution of the fuel assemblies are assumed to be compressed to 50 atmospheres in 50 litre steel flasks.

The depleted uranium, which is a reprocessing waste in some fuel cycles is converted into uranium dioxide. Using 5.0MT/m^3 for the packed density the number of drums given at item 4 of Table 8 could be calculated.

Medium-level and plant maintenance wastes taken together at item 5 of Table 8 of mainly consist of solidified concentrates, ion-ex-change resins, iodine absorbers and contaminated equipment, and are assumed to be packed in shielded or unshielded 200 litre steel drums in the fractions of 60% and 40% respectively. The 1% plutonium loss in reprocessing is distributed as 0.5% in vitrified waste, 0.3% in hulls, and 0.2% in

medium level wastes.

Low-level wastes, item 6 of Table 8 mainly consisting of exhaust air filters and general trash, and the plant decommissioning wastes, item 7, are both packaged in 200 litre drums. The numbers of drums are taken as 90% unshielded and 10% shielded.

For the design of a deep underground repository for the high-level wastes, and for the assessment of the health and safety impact, an inventory is needed of all the radionuclides which are to be disposed of in significant quantities. The dominant contribution to this inventory is made by the fission products and the transplutonium elements in the waste forms listed in Table 7 and Table 8. These waste forms also contain uranium and plutonium in quantities that vary widely from one fuel cycle to another. Since emplacement of the conditioned spent fuel and the various forms of reprocessing waste is assumed to take place 10 years after discharge from the reactor, it is sufficient to evaluate the radioactivities at that time. The figures for the five fuel cycles are given in Table 9.

Table 9. Radioactivity (Ci) in Spent Fuel Waste and Vitrified Reprocessing Waste Per GWa of Electricity (After 10 Years)

Radionuclide	Half-life, years	LWR		HWR		FBR
		Once -through	U-Pu cycle	Once -through	U-Pu cycle	
^{85}Kr*	10.8	2.0E5	1.8E5	—	—	1.0E5
^{90}Sr	28.1	2.0E6	1.8E6	2.3E6	1.7E6	9.8E5
^{99}Tc	2.1E5	5.0E2	5.0E2	2.1E2	5.4E2	4.5E2
^{129}I*	1.7E7	1.3E0	1.3E0	1.2E0	—	8.4E1
^{134}Cs	2.05	2.9E5	3.3E5	9.1E4	1.7E5	3.1E4
^{135}Cs	3.0E6	8.2E0	1.2E1	3.8E0	5.0E0	3.4E1
^{137}Cs	30.0	2.9E6	2.9E6	3.3E6	3.3E6	2.8E6
^{147}Pm	2.62	2.5E5	2.3E5	8.6E5	6.4E5	6.5E5
^{154}Eu	16.0	1.6E5	2.2E5	7.3E4	1.3E5	2.9E5
^{234}U	2.6E5	2.6E1	2.8E1	5.1E1	2.0E1	2.0E1
^{235}U	7.1E8	5.5E1	6.0E3	9.3E1	2.2E1	8.0E4
^{236}U	2.4E7	9.6E0	1.0E1	8.2E0	1.5E2	2.6E3
^{238}U	4.5E9	1.1E1	1.2E1	5.9E1	2.5E1	7.0E2
^{237}Np	2.1E6	1.3E1	1.5E1	3.4E0	3.7E0	3.9E0
^{238}Pu	89.0	9.3E4	2.2E3	9.0E3	4.4E2	1.1E4
^{239}Pu	2.4E4	1.1E4	1.8E2	2.9E4	1.4E2	1.3E3
^{240}Pu	6.8E3	1.6E4	2.0E2	3.8E4	5.8E2	1.8E3
^{241}Pu	14.6	2.2E6	4.4E4	1.9E6	3.8E4	1.3E5
^{242}Pu	3.8E5	5.0E1	1.0E0	3.1E1	7.3E0	5.3E0
^{241}Am	433	4.8E4	1.7E4	3.9E4	8.0E4	7.7E4
^{242}Am	152	2.7E2	1.3E3	2.0E1	1.3E2	3.5E3
^{243}Am	7.7E3	6.5E2	2.8E3	6.3E1	8.6E3	1.5E3
^{242}Cm	0.45	2.2E2	1.1E3	1.7E1	1.1E2	2.9E3
^{243}Cm	32.0	1.1E2	3.0E2	1.6E1	6.7E2	1.4E3
^{244}Cm	18.1	6.1E4	5.8E5	1.3E3	8.9E5	3.4E4

* Not in vitrified waste.

Table 10. Reference Containers for Packaging Wastes.

Identification	Internal diameter, cm	Height, cm	Wall material	Wall Thickness, cm	Loading capacity
Drum, unshielded	Variable		Carbon steel	0.16	0.20m^3
Drum, shielded	Variable		Carbon steel	0.16	0.20m^3
			Concrete	20	
Canister PWR	32	490	Steel	1.3	1 PWR assembly
Canister BWR	41	490	Steel	1.3	3 BWR assembly
Canister HWR	86	115	Steel	2.5	72 HWR bundles or 0.60m^3
Canister HLWs	30	300	Stainless steel	1.0	0.177m^3
Canister HLWg	20	300	Stainless steel	1.0	0.077m^3
Gas Flask	—	—	Steel	—	0.05m^3

3.7. Reference Waste Containers

Various types of packaging containers have been referred to in the foregoing tables of fuel cycle wastes. Further information on these containers is given in Table 10.

3.8. Transport of Waste

Except for the uranium mill tailings, which are conveyed as a slurry to a tailings area in the immediate vicinity of the extraction plant, all the other wastes are assumed to be packaged for transport to a storage site remote from the plant.

It is generally considered mandatory that for ultimate disposal the spent fuel assemblies or the vitrified reprocessing waste be isolated in a repository deep underground. For the less radioactive forms of waste, most nations practice other methods such as shallow land burial or ocean disposal. In this study, however, it is assumed that all the packaged wastes are transported to the site of an underground repository. The gas flasks are retained in an engineered store at the surface on the repository site until the repository is closed. All other packaged wastes are emplaced underground, if necessary after a period of cooling in a special interim storage facility. It is assumed that all packaged wastes have to be transported over land for a distance of 500 Km.

The reference logistics are shown diagramatically in Figure 6, and the numbers of packages of different types for each of the fuel cycles are summarised in Table 2. For an appreciation of the transport requirements it should be noted that the spent fuel and HLW canisters require transport casks of very special design because of

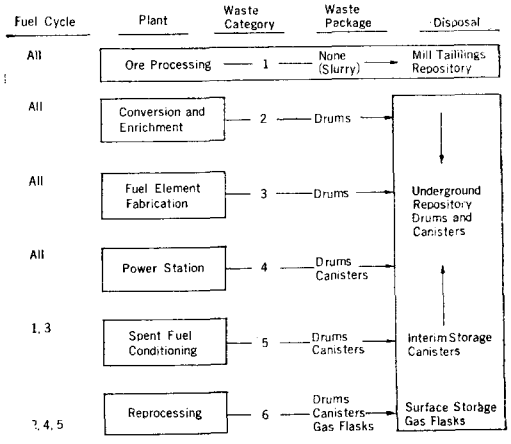

Fig. 6. Waste Mangement Logistics. Blocks Represent Separate Sites

Fig. 6. Waste Management Logistics. Blocks Represent Separate Sites

Table 11. Integrated Decay Heat (KW/year) Per GWa of Electricity.

Years after vitrification or encapsulation	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
10	370	460	360	570	260
30	910	1030	890	1310	630
100	1920	1750	1880	2310	1250
300	3090	2090	3100	3060	1890
1000	4880	2380	5500	4040	2740
3000	7150	2760	9840	5160	3430
10000	11200	3450	19700	6910	4200

their high radiation intensity, whereas the other package types do not.

3.9. Decay Heat and Interim Storage

The spent fuel and vitrified reprocessing waste stand out among the other waste arising by their release of decay heat. Some values of the integral heat release from 10 years after reactor discharge are listed in Table 11.

The decay heat data relate to repository design but also must be taken into account in the design of such storage facilities as are needed to allow flexibility in management and transport of spent fuel and vitrified reprocessing waste.

Interim storage of these wastes could also be used to alleviate the initial heat loading problem on emplacement in a geological repository. The reductions in geological repository space that would be attained by such additional storage over 30 years are as much as 50%, which has a considerable effect on costs.

3.10. Waste Repositories

It has been said earlier that in this study all packaged wastes are assumed to be placed in a repository located deep underground in a suitable geological formation.

Overall safety considerations and the particulars of any nuclear economy will dictate whether specific repositories should be used for the various waste types or whether a single repository should accommodate all waste types. In some fuel cycles the drummed medium level wastes may require stringent disposal conditions but, normally, safety considerations would not require that they be emplaced at the same depth and in the same type of repository as high-level waste and spent fuel.

In Table 12 a distinction has been made between the heat producing canisters and all other wastes. This table gives the repository storage area required in hectares for the solid wastes arising from the various fuel cycles. Since the packaging design for storage in a repository in hard rock requires more space than that for a repository in salt, two sets of figures for storage area are given in Table 12. It has already been mentioned that additional interim storage of 30 years would reduce these required areas by up to 50%.

4. Health and Safety Impacts

For each of the fuel cycles, an estimate has been made of collective dose commitment due to the radioactive wastes arising from the generation of 1 GWa of electricity,

Table 12. Projected Underground Disposal Area Required Per GWa of Electricity.

Type of repository Type of waste	Unit of Area	LWR		HWR		FBR
		Once through	U-Pu cycle	Once through	U-Pu cycle	
Repository in sait						
Heat producing	ha	0.28	0.15	0.50	0.27	0.18
Other	ha	0.12	0.16	0.11	0.17	0.13
Total	ha	0.40	0.31	0.61	0.44	0.31
Repository in hard rock						
Heat producing	ha	0.66	0.59	0.58	0.59	0.47
Other	ha	0.21	0.28	0.19	0.31	0.18
Total	ha	0.87	0.87	0.77	0.90	0.65

based on the method of waste management and disposal.

The basic concept for this assessment is the effective dose equivalent as defined by the International Commission on Radiological Protection. This is a properly weighted average of dose equivalents received by different body tissues of an individual. For a population this concept leads to that of the collective dose equivalent, which is the sum over all members of that population of the effective dose equivalents received.

Sometimes a population becomes committed to receive a radiation exposure by the introduction of a practice or some other finite originating event. The exposure could be delivered over a considerable period of time after that event. To have a measure of the total exposure of the population, the collective dose equivalent commitment is used. This is the time integral of the collective dose equivalent rate from the time of the originating event to infinity. In this assessment the shorter term collective dose commitment will be used. The event considered will always be the disposal of waste arising from the generation of 1 GWa of electricity. Therefore, the final results will be expressed as the collective dose commitment in units of 1K man-rem per GWa of electricity.

The concept of collective dose commitment should be applied with caution since it implies a comparative judgement of the importance of detrimental effects at present or in the near future and those which conceivably might be induced over a very long time span in the very far future. It gives the same weight to present and very far future detriments, which is not the usual practice in other types of human judgements. Furthermore, as little is really known about the environmental parameters which will govern the far future exposures, considerable uncertainly is attached to the assessment.

4.1. Migration of Radionuclides from Repositories

The collective dose commitment from radionuclides emplaced in a repository will depend on the time after which, and the way which they reach man. Therefore in this section the principles are discussed by which the contributions to the collective dose commitment can be calculated for releases to air (4.1.3), to fresh water (4.1.4) and to the ocean (4.1.5).

4.1.1. Mill Tailings Repositories

From the previous discussion of the radi-

onuclides in the residues of ore processing (3.1) it has been pointed out that they release ^{222}Radon. With the short half-life of this nuclide, 3.8 days, only part of the emanation reaches the atmosphere. For an infinitely thick layer of the tailings the release rate is estimated at 5×10^{-10}Ci/m^2 per second. It should be recognised, however, that differences in emanation could be observed between arid and humid areas from different types of ore. The earth cover of 2m over tailings piles is assumed to reduce the emanation by a factor of about 4.

The emanation could conceivably continue for several hundred thousand years as the activity of ^{226}Ra is in equilibrium with that of ^{230}Th. However, the continued presence of the tailings pile on the surface with the presence of these parent nuclides for such long periods seems unlikely. Since eventually the area will either be eroded and the materials transported finally into water, on in some cases continually covered with further dust. In this study it is assumed that the mean residence time of radium in the mill tailings is 1000 years, the element being gradually removed from the tailings area to circulating waters.

4.1.2. Geological Repositories

The first two barriers against the migration of radionuclides buried in the geological formation are provided by the matrix in which they are embedded and by the canister in which this matrix is contained. In this assessment the life of the stainless steel containers is assumed to be 1000 years, and the retention time in an oxidic or vitreous matrix is 10,000 years. The results of the analysis do not depend critically on these assumptions with respect to engineered barriers since much longer time constants are assumed for the geological barriers. The latter have to be considered separately for a repository in salt and one in hard rock.

4.1.2.1. Salt Repository

In a salt repository the waste packages would not be exposed to ground water unless due to some disruptive event. The probability of such an event is considered to be small on a time scale less than 10^4 years, but assumed to approach one on a time scale 10^6 years. After such an event it would still take considerable time for the the water to reach the surface. A period of 10^5 years may therefore be considered a conservative estimate for the time it would take for any contaminated water to travel from the buried waste to the surface. Although some radionuclides, such as ^{129}Iodine would travel with the same velocity as the water, others would be delayed by exchange with the soil. This delay would vary greatly between nuclides and would also be site-specific. For this assessment, therefore, two cases are considered. In one no delay is considered so that the undisturbed mixture of radionuclides reaches the surface water 10^5 years after burial. In the other a uniform delay factor of 10 is assumed, so that the undisturbed mixture reaches fresh water after 10^6 years.

4.1.2.2. Hard Rock Repository

In a hard rock repository, the waste canisters would be in contact with water but the flow velocity of this water would be very low. The transport of any dissolved nuclides through the buffer material (bentonite) surrounding the canisters will be governed by diffusion which is very slow. Movement of most radionuclides will be strongly retarded by chemical interactions with the buffer material and with the host

rock. For a collective dose assessment it has been assumed that all radionuclides in the waste are dissolved and travel to the biosphere together. As for the salt repository, therefore, the analysis also in this case is performed assuming that the undisturbed mixture of radionuclides enters fresh surface waters after either 10^5 or 10^6 years.

4.1.3. The Atmospheric Pathway

The radon emission from a mill tailings area of given size can be calculated by using the figure given in 4.1.1. of 5×10^{-10}Ci/m^2 second. As the average radon emission of the earth land surface is known, one can convert this source strength to the equivalent area of land. Using the known contribution that radon makes to the average radiation exposure and assuming a constant average density of population, one then calculates the collective dose commitment from the tailings pile per unit of time.

4.1.4. The Freshwater Pathway

When a known amount of radionuclide is released to a body of water of given volume, one may compute the time integral of the concentration from the known radioactive decay constant (which for the surving radionuclides is small) and the turnover time of the receiving water, which in this study is assumed to be 10 years. The simplifying assumption is made that the number of people drinking water or consuming fish from a body of water is proportional to its volume. Considering the world as a whole one then finds that the world population annually drinks a fraction 2.7×10^{-5} of the available fresh water and consumes 3×10^{-8} of its fish content. Using these figures together with the effective dose equivalent per unit of activity ingested for each nuclide and the concentration factors for drinking water and fish, the collective dose commitment may be obtained for the releases to fresh waters as considered in this study.

4.1.5. The Ocean Pathway

As mentioned before, a basic assumption for this study is that the complete inventory of radionuclides (Table 9), which are all long lived, released from a repository will eventually reach the ocean. It is furthermore assumed that this will lead to a uniform concentration, the time integral of which for a given release may be found from the combined time constants of radioactive decay and sedimentation. Contrary to the fresh water pathway where the short turnover time made contributions of long lived daughters insignificant, one has to take them into account for the ocean. Also the fact must be considered that some daughter nuclides are less retained by sediments than the parent nuclide. As for fresh waters for the calculation of the collective dose commitment one must take into consideration the exposure through the consumption of fish and other sea food but in addition, sediment re-suspension and inhalation and external exposure to sediments.

4.2. Assessment of the Collective dose Commitment

The contribution of the different waste categories to the collective dose commitment will now be considered. Apart from the mill tailings two values are given for each waste category corresponding to the assumptions made on migration from geological repositories (salt and hard rock).

4.2.1. Wastes from Ore Processing

The areas of land committed to mill

Table 13. Surface Area Requirement of Waste Management of Mill Tailings Per GWa of Electricity.

	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
Area committed to Tailings ha	1.46	0.85	1.27	0.53	0.0086

Table 14. Contributions of Uranium Mill Tailings to Collective Dose Commitment Per GWa of Electricity (Kman-rem).

	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
Through air	1.0	0.6	0.8	0.4	0.005
Through water	36	21	32	13	0.2
Sum total	37	21.6	32.8	13.4	0.205

tailings repositories for the five fuel cycles is given in Table 13.

From the mill tailings area per GWa, the radon release figures (4.1.3.), the assumption of 1000 years for the presence of radon precursors in the tailings pile, and the methodology explained in 4.1.3. one can calculate the contribution through lung exposure from radon emanation, listed in the first line of Table 14. The models sketched in 4.1.4. and 4.1.5. are used to calculate the contribution through fresh water and ocean pathways, assuming that all radium moves from the tailings to fresh waters after 1000 years, and this gives the second line of figures in Table 15. The passage of ^{226}Radium through fresh water only accounts for 76% of these values.

This table shows that the radon release from the undisturbed tailings piles makes only a minor contribution to the total effect.

4.2.2. Total Collective Dose Commitment

The collective dose commitment from waste disposal in each sector of the fuel cycle together with the total collective dose commitment for each fuel cycle is given in Table 15. However one should not forget that there is a finite collective dose commitment from the natural occurrence of uranium if it were not processed for use in nuclear power generation. At the bottom of Table 15, therefore, figures are included for the total collective dose commitment due only to the nuclear fuel cycle wastes, by the subtraction of the dose commitment input from the originating quantity of natural uranium.

4.3. Occupational Risks

So far this study has dealt with the radiological impact of waste management and disposal on the health and safety of the public. To estimate the occupational health and safety impacts it is assumed that the procedures and installations are designed to limit the maximum individual exposure to 5rem/year. In practice the average annual dose equivalent will be 10% of this at 0.5 rem/year. In waste management and disposal for the various fuel cycles it is assumed that the number of workers for an installed capacity of 50 GW is 1000. Thus the occupational component of the collective dose commitment should be of the order of

Table 15. Summary of Collective Dose Commitments (Kman-rem) from Waste Disposals Per GWa of Electricity.

Wastes	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
1. Ore processing wastes	37	22	33	13	0.2
2. Refining and conversion	27	16			
and enrichment wastes*	9.0	5.9			
3. Fuel element fabrication	<0.1	<0.1	<0.1	<0.1	0.1
wastes*	0.1	0.1	<0.1	0.1	0.3
4. Reactor wastes	<0.1	<0.1	<0.1	<0.1	<0.1
5. Unreprocessed	8.9	—	31	—	—
Spent fuel*	27	—	45	—	—
6. Reprocessing wastes*	—	3.07	—	13.7	1.8
Sum total*	73	41	64	27	2.2
	73	33	78	25	5.8
Sum total after subtraction of	40	23	34	14	2.1
Contribution of input uranium*	57	25	61	18	5.4

* Upper and lower figures for migration times of 10^6 and 10^5 years.

10 man-rem/GWa. Even with the qualifications one should attach to the collective dose commitments in Table 15 this contribution is negligible.

5. Costs

I am usually reluctant to introduce costs into a comparative study of this nature, because the numbers generated in any cost assessment are specific to the circumstances pertaining at a particular point in time and to the ground rules laid down for their calculation, which are certainly changeable over time. Nevertheless for use purely as a means of comparing fuel cycles there is some merit in examining this aspect, provided that the same ground rules for calculating costs of waste management and disposal are rigidly applied to each fuel cycle.

In estimating the cost of waste management and disposal for these fuel cycles no resource value was assumed for spent fuel nor for recycle materials. In addition values for a large number of other parameters had to be assumed. Thus an annual wage rate of US $ 35000, an electrical energy rate of US $ 0.10/KWh, and a life of 15 years for transport containers were adopted. Percentage rates were assumed for repair and maintenance, for insurance, for administration, for back-filling, decommissioning, and for research and development. The resulting figures are summarized in Table 16.

6. Summary of Estimated Impacts of Waste Management

The various impacts from waste management and disposal that have been examined in this study are summarized in Table 17.

Table 16. Cost of Waste Management and Disposal in Million US $ Per GWa of Electricity for 50 GW Installed Capacity.

Description	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycles	
Mill tailings management	0.64	0.37	0.56	0.23	0.005
Conditioning and transport of other wastes for Repository in salt	4.65	5.62	4.43	4.74	4.27
Repository in hard rock	4.93	5.62	5.12	4.74	4.27
Disposal of other wastes in Repository in salt	4.10	2.98	5.06	4.11	2.88
Repository in hard rock	8.49	7.40	6.79	6.81	6.44
Total costs for management and disposal of wastes Repository in salt	9.4	9.0	10.1	9.1	7.2
Repository in hard rock	14.1	13.4	12.5	11.8	10.7

Table 17. Summary of Estimated Impacts of Waste Management and Disposal Per GWa of Electricity.

Impact	LWR		HWR		FBR
	Once-through	U-Pu cycle	Once-through	U-Pu cycle	
Land use ha	1.6	1.0	1.4	0.7	0.1
Collective dose commitment excluding imput uranium Kman-rem					
Migration time, 10^6 years	40	23	34	14	2.1
10^5 years	57	25	61	18	5.4
Costs million, US $					
Using Salt repository	9.4	9.6	10.7	9.1	7.2
Using Hard rock repository	14.1	13.4	12.5	11.8	10.7
Heavy metal requirement, MT	205.4	119.5	178.8	74.6	1.2
Cumulative heat release from spent flue or HLW, KWa					
0—100 years	1920	1750	1880	2310	1250
0—10,000 years	1120	3450	19700	6910	4200

7. Conclusions

From this study it can be concluded generally that the relative differences of the impacts from radioactive waste management and disposal between the selected fuel cycles are not decisive factors in choosing a fuel cycle. Employing the technologies assumed here, the radioactive wastes from any of the fuel cycles studied can be managed and disposed of with a high degree of safety and without undue risk to man or the environment.

More specifically, in comparing the fuel cycles it is concluded that:

1) The environmental and radioiogical impacts are mainly correlated to the uranium demand and are largest for the once-through fuel cycles, and smallest for

the FBR cycle. The land use for mill tailings is, except for the FBR cycle, dominant compared with that for the rest of the fuel cycle.

2) The estimated contribution from waste disposal to the collective dose commitment is small compared with that from natural background. In making this comparison, however, one should remember that most of the exposure from waste disposal would occur over a long period of time starting far in the future.

3) The cost of waste management and disposal is only a few per cent of the value of the electricity generated and does not vary greatly between fuel cycles.