HIGH LEVEL WASTE TRANSPORT AND DISPOSAL COST CALCULATIONS FOR THE UNITED KINGDOM

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ABSTRACT

Commercial nuclear power has been generated in the United Kingdom since 1962, and throughout that time fuel has been reprocessed giving rise to high level waste. This has been managed by storing fission products and related wastes as highly active liquor, and more recently by a program of vitrification and storage of the glass blocks produced. Government policy is that vitrified high level waste should be stored for at least 50 years, which has the technical advantage of allowing the heat output rate of the waste to fall, making disposal easier and cheaper. Thus, there is no immediate requirement to develop a deep geological repository in the UK, but the nuclear companies do have a requirement to make financial provision out of current revenues for high level waste disposal at a future repository. In 1991 the interested organizations undertook a new calculation of costs for such provisions, which is described here. The preliminary work for the calculation included the assumption of host geology characteristics, a compatible repository concept including overpacking, and a range of possible nuclear programs. These have differing numbers of power plants, and differing mixes of high level waste from reprocessing and spent fuel for direct disposal. An algorithm was then developed so that the cost of high level waste disposal could be calculated for any required case within a stated envelope of parameters. An Example Case was then considered in detail leading to the conclusion that a repository to meet the needs of a constant UK nuclear economy up to the middle of the next century would have a cash cost of £1194M (US$2011M). By simple division the cost to a kWh of electricity is £0.00027 (0.45 US mil).

GENERAL

Political and Financial Background

Commercial nuclear power generation and reprocessing have existed in the UK since 1962. The industry has created wastes which are divided into three categories:

- LLW, Low Level Waste, less than 4 GBq/Mg alpha or 12 GBq/Mg beta-gamma.
- ILW, Intermediate Level Waste, more active than LLW.
- HLW, High Level Waste, as for ILW but having a rate of heat emission that requires consideration for design of management facilities.

LLW is regularly disposed of at the engineered shallow repository at Drigg in NW England and a deep ILW repository is being developed by UK Nirex for operation from 2005. At that stage the UK will only lack a repository for HLW, currently comprising vitrified fission products and related wastes. It would also include fuel to be sent directly for disposal if such a policy were to be adopted. Government policy is that vitrified fission products and related wastes should be stored for at least 50 years, Ref. 1, and successful storage is already established technology in the UK (see section on waste management systems).

About a decade ago the UK Government sponsored some research on HLW disposal. Outline design studies were undertaken by engineering consultants and these studies considered a range of designs, for waste overpacks, handling underground, and for the repository itself in differing geologies (saliferous and argillaceous). In addition to design concepts and specifications, estimates of cost were given.

Until recently these often formed the basis of financial provision in the UK. Studies have now been carried out for new cost estimates based on some of the information gained from detailed technical work carried out for the ILW repository, with appropriate adjustments being made for the differences between ILW and HLW disposal. The results of the new study are described here in the section on cost calculations.

In the UK four organizations (AEA Technology, British Nuclear Fuels plc, Nuclear Electric plc and Scottish Nuclear plc) have liabilities for HLW prior to its ultimate disposal, and they have cooperated in undertaking the new study, as described in the section of acknowledgements. In addition to the HLW from these four organizations there are high level wastes arising from overseas reprocessing contracts secured before 1976, for which there is no provision for return of wastes and these are included in BNFL's provisions. There is also defense HLW. The companies are required to make provisions within their accounts for long term liabilities. This is consistent with the legal obligation on companies to maintain good accounting practice.

UK Nuclear Power Program

The reference UK nuclear power program comprises existing plants and one PWR under construction at Sizewell B. In addition *eight future* PWRs are added to represent a constant nuclear economy through to the middle of the next century. This gives the assumed heat load capacity on which the size of the notional repository will be based in the Example Case. The power program details may be summarized as follows:

- Magnox (Natural uranium metal fuel in magnesium alloy clad, CO_2 cooled)
  - 11 twin reactor plants operating; 2 twin reactor plants being decommissioned } Approx. capacity 4.5 GWe

- Advanced Gas-cooled Reactor (AGR) (Enriched oxide fuel, stainless steel clad, CO_2 cooled)
  - 7 twin reactor plants operating } Approx. capacity 8.5 GWe
- Pressurized Water Reactor (PWR)
  - 1 plant under construction at Sizewell B } Approx. capacity 1.2 GWe
- Experimental/Demonstration reactors:
  - 1 Fast Reactor (PFR)
  - 1 High temperature reactor (HTR) being decommissioned
  - 1 Steam Generating Heavy Water Reactor (SGHWR) being decommissioned
  - 1 Windscale Advanced Gas-cooled Reactor (WAGR) being decommissioned

HTR produced heat only. PFR, WAGR and SGHWR combined capacity approx. 0.4 GWe

- Future PWR Program:
  - 8 PWRs which are expected to give an approximate capacity of 9.6 GWe

GEOLOGICAL MEDIUM

A wide variety of geology is available in the UK. The latest work assumes a granite host geology, which can be found in some parts of the UK, and in particular assumes an unfractured granite. The assumed geological parameters are:

Depth	1000 m
Host rock temperature limit	100°C
Thermal conductivity	2.5 $Wm^{-1}K^{-1}$
Density	2650 kgm^{-3}
Specific heat	850 $Jkg^{-1}K^{-1}$
Natural heat generation	4 μWm^{-3}
Convective heat transfer	negligible

It should be noted that in practice a lower limiting temperature relating to container metal corrosion rather than host rock may appertain, particularly in cases where overpacking has not been used.

WASTE MANAGEMENT STRATEGY

There are inevitable uncertainties regarding future nuclear power programs and reprocessing policies. The approach has thus been to assume a particular nuclear power program and reprocessing policy as part of the Example Case, and also to consider the possibility of other nuclear power programs and reprocessing policies.

The Example Case is based on a constant nuclear economy as outlined in the section on power program and involves the reprocessing of all commercial fuel and that from PFR. Other fuel from non-commercial reactors (HTR and SGHWR) is assumed to be directly disposed.

The HLW from Magnox and AGR fuel reprocessing is to be vitrified and kept in the Vitrified Product Store (VPS) at Sellafield, BNFL's reprocessing site. It is anticipated that PWR vitrified HLW will be similarly managed. VPS and similar future facilities will be suitably maintained or periodically replaced, until the deep repository is in operation. For the purposes of this study the small quantities of Highly Active Liquor (HAL) at the Dounreay Research Establishment in the north of Scotland are also assumed to be vitrified, stored and ultimately disposed of.

The fuel from the HTR(Dragon) and SGHWR reactors is assumed for the purpose of this study to be stored until the repository is in operation, when it is assumed to be directly disposed of without reprocessing.

The effect of storage and hence prolonged cooling is to diminish the heat output rate of the waste, which gives the benefit of a smaller, somewhat cheaper repository, because the spacing between container disposal boreholes may be diminished without exceeding the repository host-rock temperature criterion.

The Example Case also assumes:

1. Repository closure date of 2100
2. Waste placed in containers at site of origin will be overpacked at the repository.
3. A repository solely for HLW and any fuel for direct disposal.
4. 20 year operational lifetime of the repository.

The above Example Case is reasonably prudent because the repository fixed costs are spread over the minimum number of HLW containers that could arise in the UK, given that the present level of nuclear generation is maintained to or beyond the middle of the next century. The disposal of spent fuel would significantly increase the number of disposal containers and add the heat load of the plutonium. A cost algorithm has thus been derived to allow the cost of HLW transport and disposal for this and other strategies (nuclear power programs and reprocessing policies) to be calculated; the algorithm is given in the section on cost calculations.

WASTE MANAGEMENT SYSTEMS

HLW storage technology is already well established in the UK and fuel dry storage is in use at Wylfa power station. Medium term wet storage of AGR, BWR and PWR fuel takes place at Sellafield, which is also where fission products and related wastes have been stored for more than three decades as HAL. Vitrification and use of the VPS began in July 1990.

It is assumed for this study, that at some time during the storage period of fuel destined for direct disposal, plants will be built on some of the storage sites to package the fuel into containers. The plant functions could well include dismantling, pin cutting (if necessary) and encapsulation. The notional intention for current costings is that all such fuel would go in stainless steel containers of the same general design as contain the vitrified waste blocks. At the time of implementation the relative merits of pin-cutting on the one hand, or special packages and special handling equipment in the repository on the other hand, will be optimized. However neither the costs of vitrifying HAL nor the costs of encapsulating fuel in containers are included in the figures given here. The assumption here for directly disposed spent fuel is that once in the containers, no special handling equipment would be required; it would be handled in exactly the same way as the vitrified waste containers. The glass block has a volume of 150 liters and the container an external cylindrical volume of just less than 200 liters.

Containers are assumed to be transferred from site of origin to the repository in a modified fuel flask with an insert supporting three circular clusters of seven containers. Flask transport is likely to be by rail.

The repository surface establishment (or Headworks Site) is shown on Fig. 1. Here the containers would be placed into 65 mm thick mild steel overpacks. The overpack acts as a corrosion retarding barrier. The overpacked container would then be placed into the site transfer flask. The disposal costs of containers with and without overpacks can be determined from the cost algorithm as given in the section on cost calculations.

The repository surface facilities would be connected to the disposal level, 1000 m below ground, by a 6 m diameter service shaft and a 8 m diameter hoist shaft for lowering the waste. A schematic diagram of the disposal level is shown on Fig. 2, while details of the two alternative waste emplacement boreholes (for use by overpacked and non-overpacked containers) in the tunnel floor are shown on Fig. 3.

The repository operating lifetime for the Example Case is a realistic figure of 20 years, but a longer operational phase of 50 years has also been assessed, for options which require flexibility on HLW disposal date. Even allowing only 20 years for all disposals none of the plant has to operate at an unrealistically high rate. After the operational phase the repository would be back-filled and sealed.

THE WASTE

Estimates of the quantity and heat output of the spent fuel and vitrified HLW are essential inputs to the cost assessment. The quantity of containers for disposal sets the scale of the transport, packaging and disposal operations and the heat output is a major factor in determining the size of the repository.

The amounts of spent fuel and VHLW for the Example Case (from the section on UK nuclear power program) and corresponding heat outputs for various time-scales are summarized in Table I.

COST CALCULATIONS

The total cost of the repository for the Example Case has been estimated by considering the following steps and components in high level waste management:

1. Front End Procedures
   - Site Investigations (including geotechnical work)
   - Engineering Costs (excluding detail design)
   - Research and Development
   - Underground Laboratory Marginal Construction Cost and Operation Costs
   - Transport and Packaging Studies
   - Public Relations
   - Public Inquiry
   - Company Administration and Staff Costs
2. Transport
   - Flasks
   - Rail Wagons
   - Loading Costs
   - Movement Costs

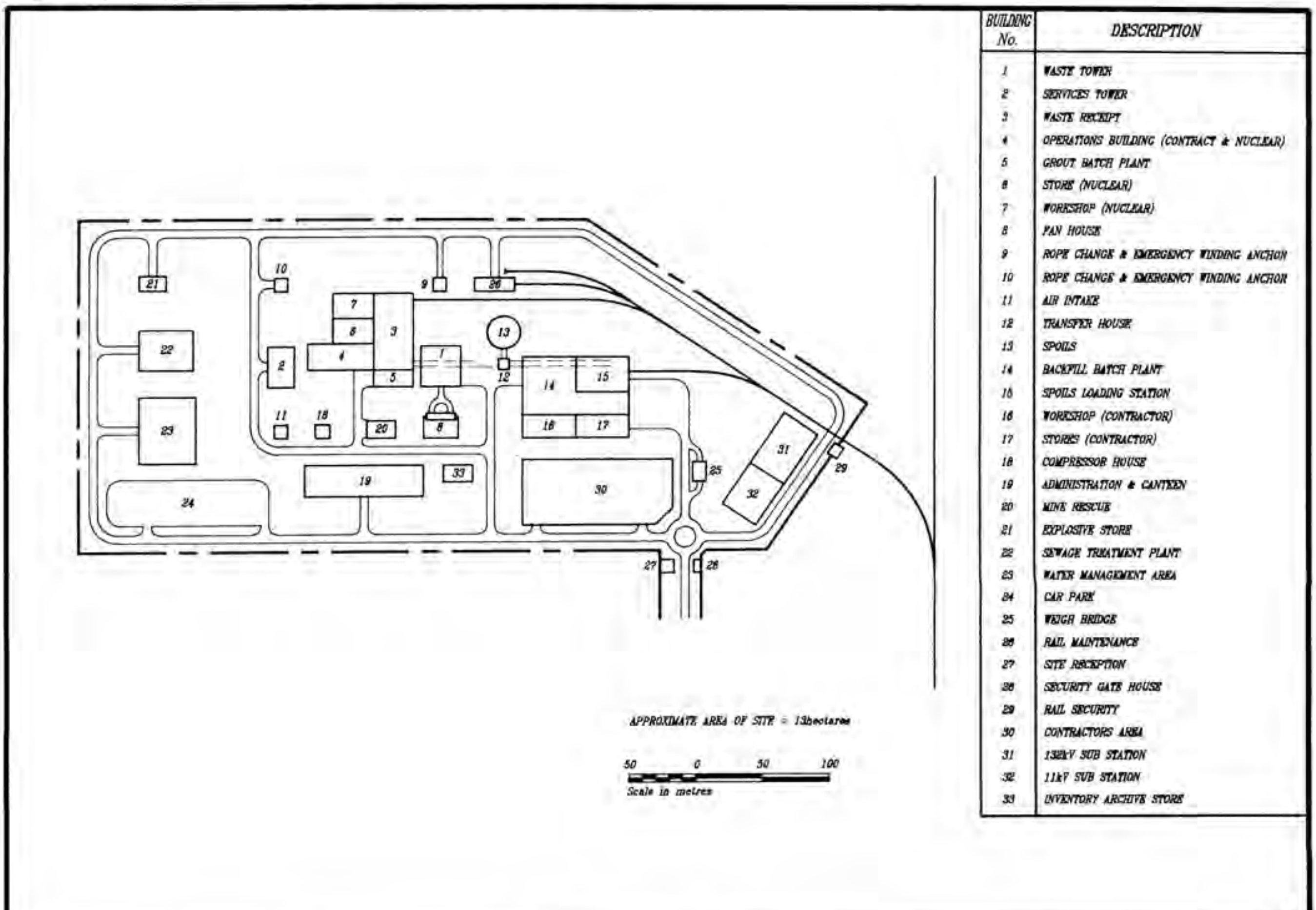

Fig. 1. Headworks site layout.

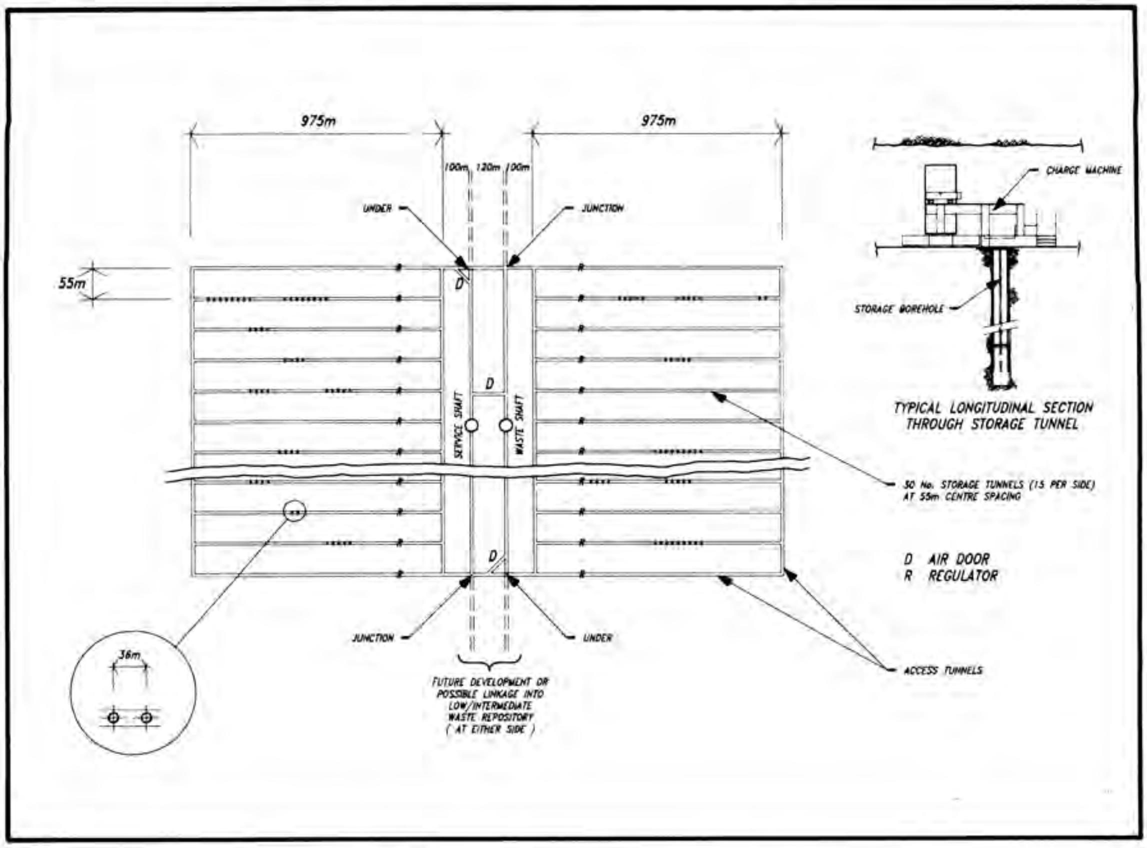

Fig. 2. Layout of underground repository.

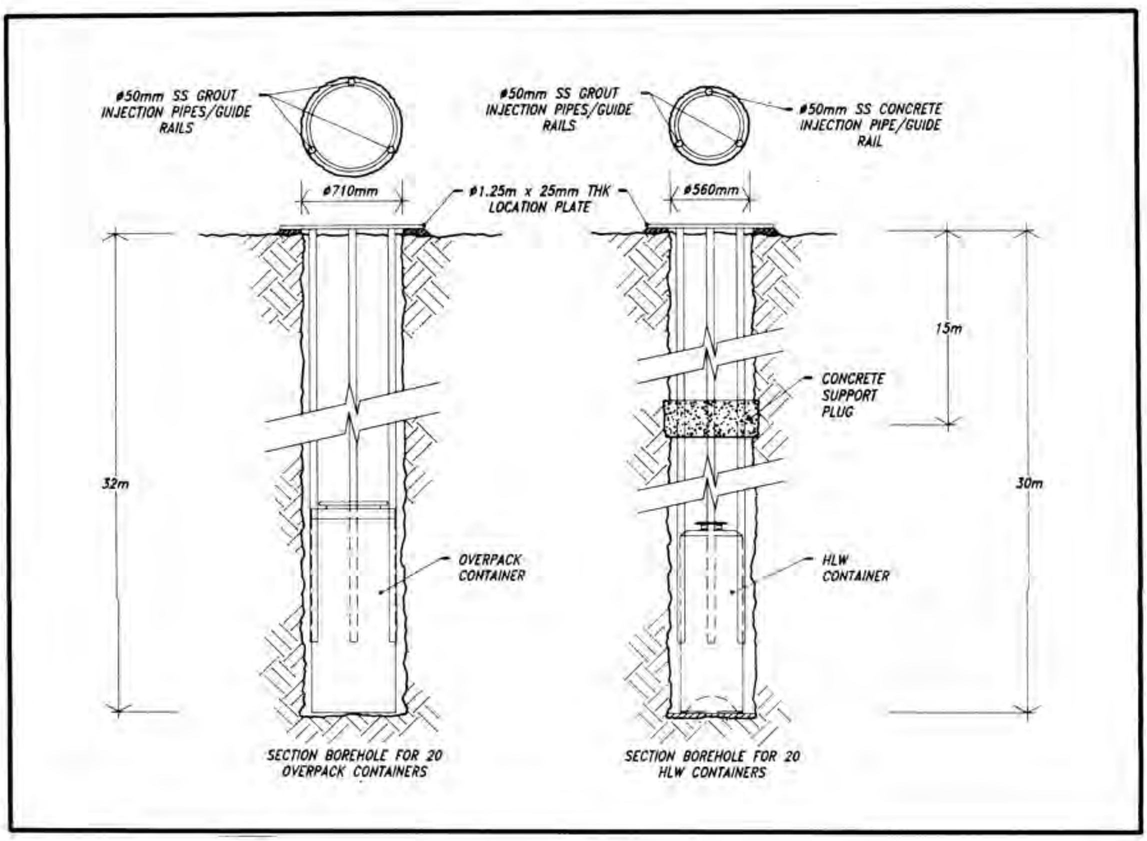

Fig. 3. Proposed repository storage boreholes.

TABLE I

UK Waste Characteristics - Container Numbers and Heat Output at Particular Dates

HLW Category	Number of Containers	Heat Output in MW		
		Year 2050	Year 2100(1)	Year 2200
Magnox & AGR (VHLW)	7720	2.70	.97	.24
One PWR (VHLW)	670	.60	.20	.05
PFR(VHLW), HTR & SGHWR (spent fuel)	820	.10	.09	.06
PWR & BWR(VHLW)(2)	600	.30	.14	.07
Future 8 PWRs(VHLW)	5360	6.20	2.20	.46
Total	15170	9.90	3.60	.88

Notes :
1. Repository closure date for the Example Case.
2. Indicative data for wastes arising from overseas reprocessing contracts secured before 1976, for which there is no provision for return of wastes.

Legend:
- AGR Advanced Gas-cooled Reactor
- BWR Boiling Water Reactor
- HTR High Temperature Reactor (Dragon)
- PWR Pressurized Water Reactor
- SGHWR Steam Generating Heavy Water Reactor
- VHLW Vitrified High Level Waste

3. Overpacking
   - Overpack procurement
4. Headworks Costs
   - Site Preparation
   - Buildings and Equipment
   - Services (Water, Sewerage, Electricity etc)
   - Salaries and staff overheads
   - Decommissioning
5. Underground Works
   - Shafts and associated infrastructure
   - Access tunnels
   - Storage tunnels
   - Boreholes
   - Final Back-filling and Sealing

These cost items can be set out in a cash-flow where the waste volume disposed of is also discounted as a surrogate for income. When the net present value (sum of discounted expenditures) has been divided by the net present volume (sum of discounted volumes disposed of) the levellized unit cost is obtained. The calculation is independent of the base date chosen; although it must be the same for costs and volumes. The calculated levellized unit cost gives an indication of what a debt-financed repository company should charge its customers to achieve ultimate break-even. In this context the discount rate applied in the calculation is synonymous with the Internal Rate of Return. The choice of discount rate would depend on the financial practice in a particular organization. At present in the UK between 2% and 5% would cover financing, depending on the financial standing of the borrower. Financing and company profit together would require a discount rate in the range 8% to at least 12%.

Once the repository company charge has been estimated as above, that charge is discounted back to the present at 2% per annum for provisions.

A cost algorithm Eq. (1) has been derived, based on the above component cost items. These are aggregated into volume dependent, time dependent, heat dependent and fixed terms to give an algorithm that can then be evaluated for any required case, be it the Example Case or any other. The cost described is the base cost plus contingency. Contingency is the additional expenditure that experience shows necessary to turn an estimate into a viable budget for a project. It allows for minor omissions and the resolution of small difficulties in the project. The data provided here or calculated from the algorithm do not include risk margin to cover changes in specification, changes in cost when the specific site and geology have been chosen, or major market movements in contractor charges.

Depending on accounting policy some organizations do add a further percentage to base and contingency for such risks. Given the level of development of the estimate it is believed that 33% is currently appropriate.

The costs calculated from Eq. (1) and all other costs presented in this paper are in 1991 money value.

Total Cost in Millions US$

$$= N(0.0174-0.00436P) + H(0.254-0.170P) + t(0.842+5.15D) + (531+871D-10.3P) \quad \text{(Eq. 1)}$$

Where:

N = number of containers

H = total heat output in kW at repository closure

t = repository operating life-time in years

And where the absence or presence of particular items is indicated thus:

D = 1 for a purpose built HLW only repository

D = 0 for the marginal cost of an HLW scheme at an ILW repository site

P = 1 where 65 mm steel overpacks are used

P = 0 where containers are emplaced without overpacking

The algorithm was developed for ranges of the variables set out below. Calculations made with the variables set beyond these ranges should be treated with caution.

$9820 \leq N \leq 36060$

$1400 \leq H \leq 12400$

$20 \leq t \leq 50$

The algorithm relates to its original form by adding 2.76% escalation from the beginning to mid 1991, and using an exchange rate of £0.61/US$. No allowance for differing purchasing parities has been made.

SPECIFIC RESULTS

The Example Case assumes disposal of 15170 overpacked containers in a purpose built repository for the sole use of HLW, operating from 2081 to 2100, with a heat output at closure of 3600 kW. The costs of the Example Case are presented in Table II. As with the costs from the algorithm, contingency is included at various rates for different sorts of costs equivalent to an average of 25% overall. The risk margin described in the section on Cost Calculations has not yet been added to the cost data in this section.

The total cost of £1194M {≡US$2011M} is equivalent to £79 k {≡US$133 k} per container disposed of. This corresponds to a volume unit cost of £394 k/m^3 {≡US$663 k/m^3} when based on the container external volume and to a volume unit cost of £524 k/m^3 {≡US$884 k/m^3} when based on the glass volume alone.

On a discounted and levellized basis at 5% the unit cost for HLW transport, overpacking and disposal costs:

£815 k/m^3 (external container volume) {≡US$1373 k/m^3}

TABLE II

Repository Costs - Major Components and Totals
Base Cost Plus Contingency, Excluding Risk

Major Cost Components	£M 1991 Money Value	US $M 1991 Money Value
Front end (including underground lab)	450	758
Packaging	29	49
Transport	12	20
Headworks (including Inventory Archive)	311	524
Underground works	392	660
Total	1194	2011

The electricity anticipated to be produced in the UK from all committed reactors is approximately 2000 TWhe, electricity associated with the overseas waste adding 10% and in addition the 8 further PWRs will produce 2160 TWhe, totalling 4300 TWhe. It follows that the charge to a kWh unit of electricity is £0.00027 {≡0.45 US mil} on a simple division basis. A more realistic approach is to take the future cost of HLW, given as £815 k/m^3 above, discount it back to the present at 2% per year and divide it by the present worth of the electricity associated with it, also discounted to the same base date at 2% per year. By this calculation the levellized charge to a kWh is £0.0001 {≡0.17 US mil}.

Deriving and using the algorithm has been very useful in clarifying what will lead to the most cost effective strategy. The front end and fixed capital costs of the repository form a large proportion of the overall cost and thus should be spread over as much waste as possible. The assumption of a constant UK nuclear economy (as opposed to committed plant only) has helped in this respect. A further possibility that has been considered but not used in the Example Case is that there will be a requirement for an ILW repository at the same time as the HLW repository. This would allow much of the expenditure on Public Inquiry, geotechnical work, transport and general infrastructure, surface site, access to the disposal level, etc to be shared between the two waste types. Such ILW could arise from a future nuclear power program and from the delayed Stage 3 decommissioning of existing reactors.

The direct disposal of fuel increases the actual costs of disposal substantially because the fuel gives rise to many more packages than the associated vitrified fission products and related wastes; also the plutonium adds appreciably to the quantity of heat to be disposed of.

Salaries and services are a substantial fixed operating cost for the repository company. Appreciable savings may be made by having the repository open for a relatively short period. This can be achieved by careful maintenance of waste stores until an optimized date for repository operations starting, followed by waste being moved from store to repository at the greatest practicable rate, once the repository is operational. This also gives more time for interest to be earned on provisions, that is to say the net present value of the repository is diminished.

Overpacking adds substantially to the cost of HLW management. However it is seen as likely to assist the avoidance of a more restrictive thermal criterion than the 100°C maximum host rock temperature. If that is so then the extra cost is more than offset by savings on additional disposal tunnel excavation for increased spacing between boreholes.

CONCLUSIONS

The UK nuclear industry has used its most recent experience of current waste management and repository technology to devise an outline design for a high level waste repository. This has been costed and the costs used in financial calculations which permit the industry to make provisions for its long term liabilities whilst contributing a very small part to the current costs of nuclear generated electricity.

ACKNOWLEDGEMENTS

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plc. The work undertaken by AEA Technology was with the financial support of the UK Department of Energy, and in that context the results of the work do not necessarily represent Government policy.

Material from the UK nuclear industry costs study , including the tables and some other information appearing in this paper, is also being made available to OECD / NEA for their current international study on the cost of spent fuel and HLW disposal to geological repositories.

REFERENCE

1."Radioactive Waste. The Government's Response to the Environment Committee's Report", (Command 9852). Her Majesty's Stationery Office, London 1986