Electricity production and waste management: Comparing the options

An IAEA survey compares cost estimates for managing wastes from the production of electricity using nuclear and fossil fuels

by V. Tsyplenkov

Many years have passed since the advent of nuclear power was hailed as providing "electricity too cheap to meter". Nevertheless the main motivation for nuclear power development programmes is to provide an affordable and secure source of electricity both for the short and long term. The cost at which electricity can be provided is therefore a highly important issue, as is the choice of the method for calculating this cost. For many years, the relative costs of different methods of electricity generation have been estimated and compared by a wide range of organizations, including the IAEA, in order to develop a proper perspective.

Since the initial development of nuclear fission reactors, radioactive waste management has often been seen as one of the major problems of nuclear power. Concerns have extended to the costs involved, in particular the cost associated with the disposal of high-level waste or unprocessed spent fuel. This cost has been widely used, not always objectively, by opponents of nuclear power in their arguments. More recently, environmentalist organizations have started to realize that all forms of energy production generate waste and have environmental effects which may be unacceptable, if not adequately controlled. The escalation over the last few years of topics, such as the "greenhouse effect" and "acid rain", into major political issues, has led to more detailed consideration of the waste management aspects from burning fossil fuels. These have hitherto been very loosely regulated, particularly in some parts of the world. We are now at a stage where the management of wastes from nuclear power remains very highly regulated and where the regulations for the control of wastes from fossil fuel power stations are being significantly tightened. Since it is almost certain that a substantial proportion of electricity will continue to be generated from both these sources, it is an opportune time to review the waste management practices and their costs.

This article is based on a survey carried out by the IAEA of existing waste management cost estimates. A number of cost studies have recently been completed for different stages of waste management. It was considered useful to collect the results of these studies and to compare them objectively with the waste management costs of electricity production from other energy sources. The comparison can then be used to provide a correct perspective of the economic and environmental aspects of the different means of production of electricity.

The comparison is made for the costs of managing waste generated in the production of electricity from representative nuclear and fossil fuel cases. The associated costs from the third major source of electricity, hydropower, are obviously small and thus not considered here. Both fossil and nuclear fuels can be exploited in a number of different types of plants. Since it would be impractical to consider all possible variants, representative plants having a capacity of 1000 megawatts-electric (MWe) were selected for the assessment, each operating at a capacity factor of 70% for 30 years.

Nuclear and fossil fuel cycles

Fossil fuel cycle. Coal is the leading fossil fuel used for electricity generation in the industrialized world, although the share of gas is increasing rapidly. In some countries, oil is also an important fuel for electricity production, but many try to avoid its use because of possible rapid changes in the price of oil. From the standpoint of waste arisings, oil is somewhere between coal and gas. Because of this, coal and

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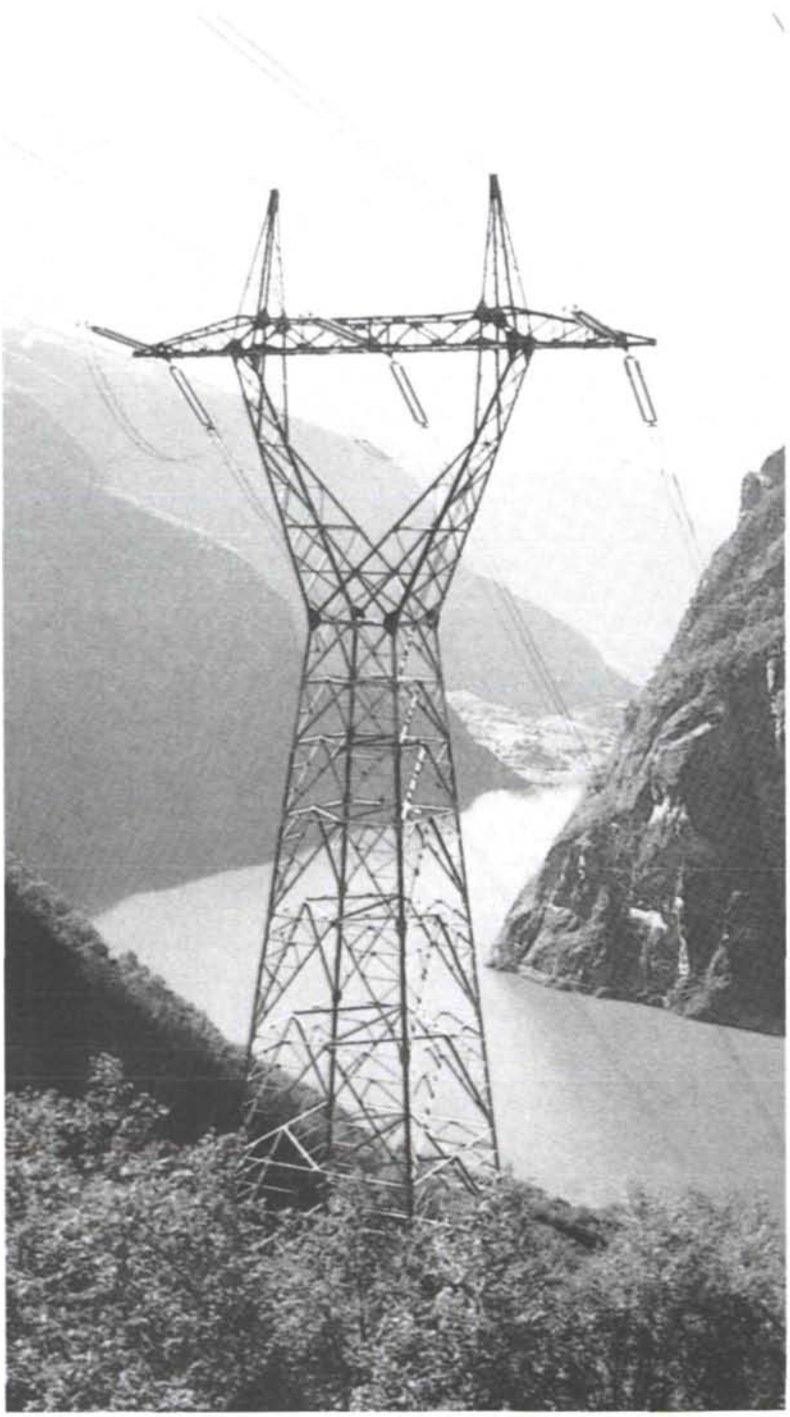
gas have been chosen as the representative fossil cases for the comparison.

Modern coal plants are fired by pulverized coal. Upon cumbustion, the coal reacts with oxygen to form carbon dioxide (CO_2). The combustion process is accompanied by the production of oxides of nitrogen (NO_x), sulphur dioxide (SO_2), fly ash, and a number of other polluting by-products including radionuclides contained in coal.



Electrical lines in Norway. *(Credit: NorEnergi.)*

For baseload electricity production, two types of gas-fired plants are available. The first is a conventional steam cycle (CSC) plant. More recent units, however, use gas turbines in front of the steam cycle to improve the efficiency of the unit; this combination is called a combined cycle (CC) plant. The combustion process of natural gas is much cleaner than coal. The main combustion products are CO_2, water, and NO_x.

A conventional coal plant and a gas-fuelled combined cycle plant are likely to be the major sources of new fossil-fuelled electricity generation. They represent both ends of the spectrum of challenges associated with waste management from fossil fuels. *(See diagram, page 30.)*

Nuclear fuel cycles. Nuclear power plants generate electricity from the heat produced when the nuclei of the atoms of heavy elements are split. The heat is used to produce steam to drive turbines which generate electricity.

Uranium is currently the principal nuclear fuel. It occurs in nature and is mined by conventional mining techniques. It is then processed into a form suitable for use as fuel in a nuclear reactor. Natural uranium contains two main isotopes, uranium-238 and uranium-235. Only the nuclei of the uranium-235 atoms are readily fissile, but uranium-235 accounts for only 0.7% of natural uranium. Some reactors use natural uranium for fuel, but most reactors now use slightly enriched uranium, in which the proportion of uranium-235 atoms has been increased (or enriched) to a few percent. Consequently, most uranium is enriched before it is fabricated into fuel elements for loading into a reactor.

When the spent fuel is removed from the reactor, typically annually, it contains unconsumed uranium, fission products, plutonium, and other heavy elements. It is possible to dissolve the spent fuel and chemically process (reprocess) it in order to extract the unused uranium and plutonium for fuel fabrication and recycling. Alternatively the spent fuel elements can be disposed of directly as waste, without reprocessing.

The two main types of fuel cycle are the once-through thermal neutron reactor cycle and the thermal neutron reactor cycle with reprocessing. *(See diagram.)* In the "once-through" thermal reactor cycle the spent fuel is not reprocessed but kept in storage until it is eventually disposed of as waste. In the thermal reactor cycle with reprocessing, the spent fuel is reprocessed and uranium and plutonium are separated from the fission products. Either the uranium, the plutonium, or both can be recycled in new fuel elements.

There are a number of thermal reactor types currently in use for electricity generation. The dominant one worldwide is the pressurized water reactor (PWR). It has therefore been selected, both with and without reprocessing, as the nuclear reference case for this comparison. Although the other types of reactors produce wastes which are different in some details to those from a PWR, it is considered that the PWR is sufficiently representative to be the reference case.

Waste arisings

Waste arises at each step of the fuel cycles: mining, fuel fabrication or preparation, power production, and decommissioning.

Electricity generation from nuclear fuel produces substantially different wastes both in quantity and type to those which arise from electricity generation using fossil fuel. The waste arisings from the operation of nuclear power plants are in the form of relatively small volumes of radioactive material. In contrast, fossil-fuelled plants burn large quantities of fuel and the operational waste arisings include large amounts of combustion products. Both types of power plants produce wastes in gaseous, liquid, and solid forms.

It is not widely appreciated that the combustion of coal releases quantities of radiation to the environment that are similar (in terms of its potential biological consequences) in magnitude to the routine releases from the nuclear industry for comparable electrical output. Natural gas production and usage also release radioactive radon to the atmosphere.

Fossil fuel wastes. Most of the wastes from fossil fuel cycles arise during power production, although for coal substantial amounts of solid wastes are also produced during mining and fuel preparation.

Combustion of fossil fuels produces carbon dioxide. Compared with coal, burning natural gas produces somewhat more than half the CO_2 on a per unit energy content basis. Coal combustion also produces oxides of sulphur (SO_2 and SO_3) while gas combustion products have almost no sulphur compounds. The combustion of coal and gas also produces oxides of nitrogen (NO_x).

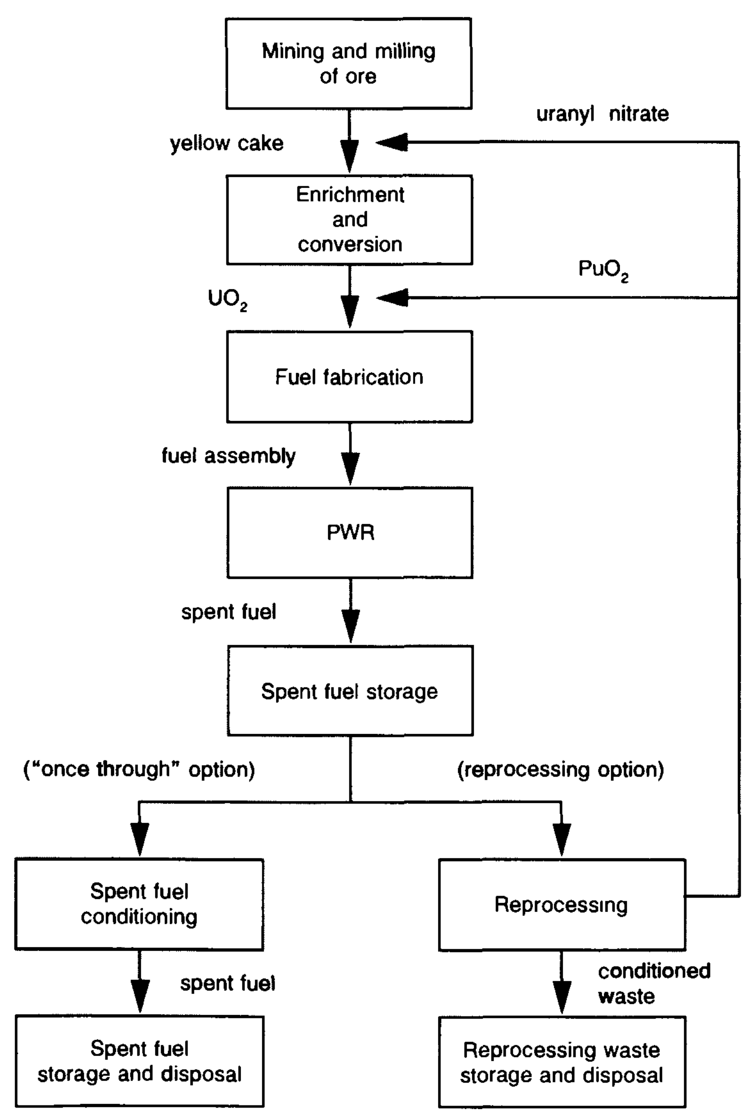
Particulate emissions (ash) also occur with the combustion of coal. Part of the ash, about 10%, remains in the boiler and is removed; this is called bottom ash. Most of the ash, however, appears as a very fine particulate material in the flue gas; this is known as fly ash.

For fossil facilities, decommissioning will likely occur soon after the end of a plant's operating life. Decommissioning wastes will generally be those associated with demolition, and would not pose special residual hazards.

Arisings of conditioned radioactive wastes

Step	Waste category	Unit	Range		
			low	reference	high
Mining and milling	LLW	m^3/a	20 000	40 000	60 000
Conversion and enrichment	LLW	m^3/a	20	20	20
Fabrication	LLW	m^3/a	20	30	30
Power plant operation	LLW	m^3/a	100	130	200
	ILW	m^3/a	50	80	100
Reprocessing	C1	m^3/a	3.5	4	4
	C2	m^3/a	20	22	25
	ILW	m^3/a	50	75	100
	LLW	m^3/a	470	580	690
Spent fuel (unconditioned and once-through)		t/a	25	30	35

Nuclear fuel cycle considered for assessment



Coal waste streams after waste treatment

	Waste streams (g/kWh)
NO_x	0.25
SO_2	0.32
Fly ash to air	0.07
Fly ash collected	3.02
Gypsum	2.10

Nuclear wastes. As in fossil fuel cycles, wastes occur at each stage of the nuclear fuel cycle.

Mining wastes consist mainly of mine waters and waste rock piles. While uranium mill tailings are generally similar to mining wastes, they contain nearly all of the naturally occurring radioactive daughters from the decay of uranium.

The conversion and enrichment processes produce solid and gaseous wastes which contain some airborne uranium. In addition, enrichment plants produce large volumes of depleted uranium which is considered as a waste for purposes of this assessment.

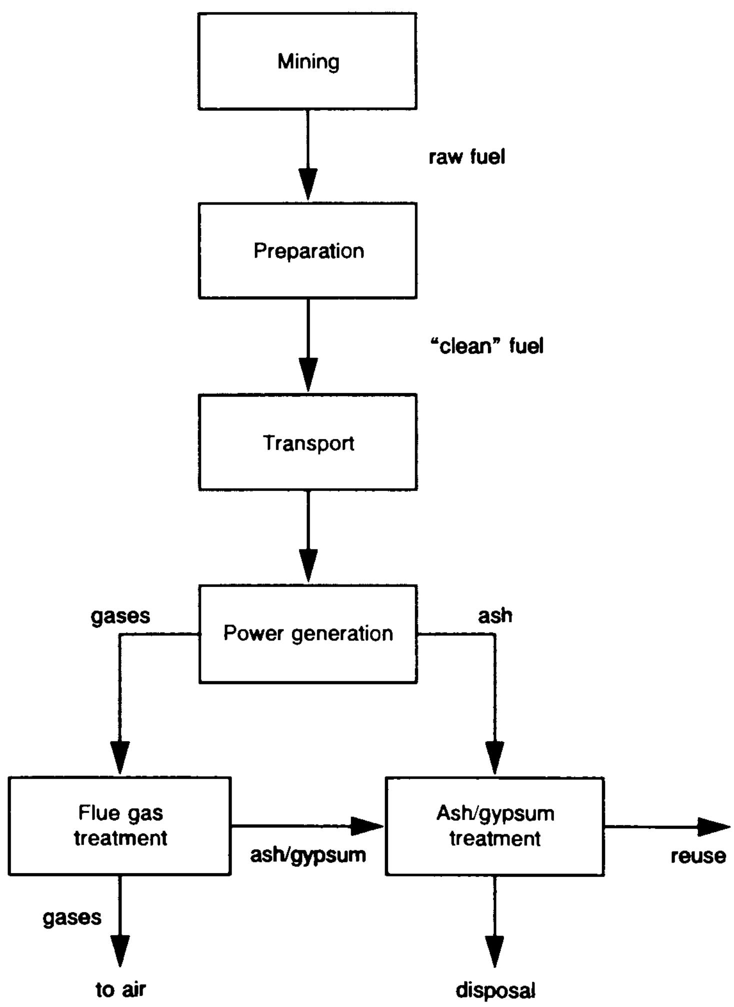
Depending on whether reprocessing is employed, fuel fabrication wastes are in the form of various solid and liquid streams contaminated with uranium and/or plutonium.

Radioactivity occurs in various liquid waste streams of the power plant. In addition, small quantities of gaseous waste are generated during reactor operation. Reactor operations also give rise to a range of solid wastes in the form of contaminated or activated components.

The radioactive content of reprocessing wastes consists largely of the fission and activation products and minor actinides that are fed into the reprocessing plant as part of the spent fuel. They occur as a variety of solid and liquid waste streams.

The radioactive nature of some of the components of nuclear fuel cycle facilities requires expensive remote handling techniques to be employed during decommissioning. The cost and need for such an approach can be reduced by delaying the work and allowing decay of radioactivity. For nuclear power plants, deferred decommissioning is a strategy commonly employed throughout the world and has been selected as the reference for the purpose of this assessment. Most of the radioactive waste from decommissioning nuclear fuel cycle facilities is low-level (LLW) solid waste. Small components of intermediate level (ILW) and high-level (HLW) or transuranic waste are associated with reprocessing of spent fuel and the fabrication of mixed-oxide fuel.

Fossil fuel cycle considered for assessment



Waste management

Fossil wastes. The largest solid waste management problem faced by the coal cycle is that related to mine spoils. These pose a significant disposal problem. One possible option includes backfilling in the mines from which they came.

The flue gas treatment in a coal plant consists of three steps: NO_x removal, SO_2 reduction, and particulate reduction. For natural gas, the only significant flue gas waste management problem currently capable of resolution is that associated with nitrogen oxides.

Modest NO_x reduction is achieved by modification of the combustion process. However the most effective process for NO_x removal is selective catalytic reduction (SCR) which uses ammonia and a catalyst to reduce the NO_x to nitrogen and water. Typical SCR reduction rates are around 80%. Used catalytic material is the only waste that requires disposal as a result of this process. However, the main component can be returned to the supplier for reuse.

Flue gas desulphurization (FGD) processes use alkaline materials to absorb and remove the sulphur dioxide from the flue gas. FGD processes tend to be large and expensive since very large volumes of flue gas containing very low concentrations of SO_2 must be treated. Large quantities of product (gypsum) result from the reaction of the sulphur dioxide and the reagent. Some of this can be treated to produce a wallboard quality gypsum and the rest is disposed of as landfill. Typical FGD removal efficiencies are 95%.

The reduction of particulate in the flue gas is usually achieved using electrostatic precipitators (ESP) which typically have a removal efficiency of about 95%. Some of the removed fly and bottom ash can be utilized in the cement and road building industries, the remainder requires disposal as landfill.

At present, there is no cost effective technology which will reduce CO_2 emissions and no attempts have been made on removal of radionuclides from gas effluents. Various waste streams are discharged into the environment after waste treatment. *(See table.)*

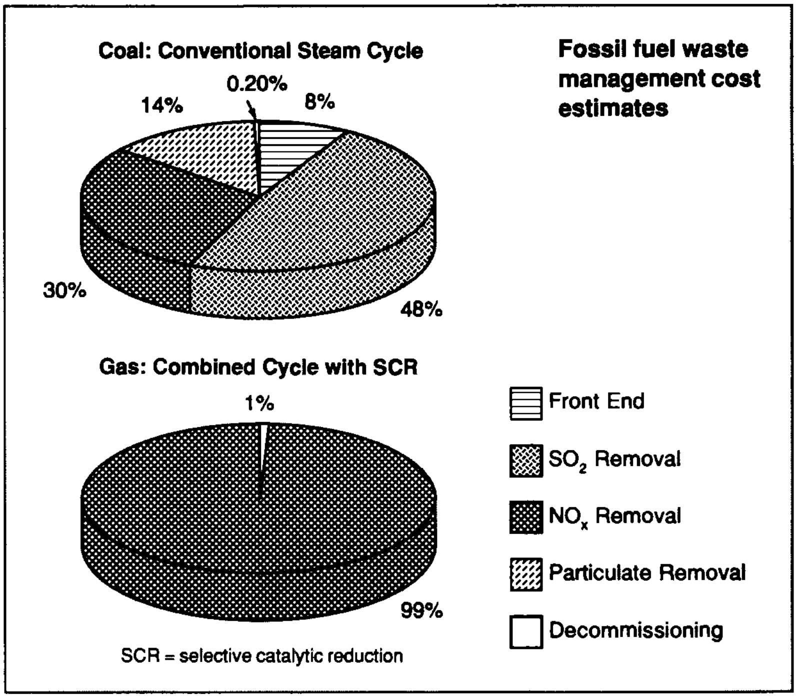
Nuclear wastes. A number of techniques are currently used in the management of radioactive wastes. These range from direct discharge to the environment (dispersal) to sophisticated techniques for immobilization of the radionuclides and their disposal in carefully designed and constructed disposal facilities.

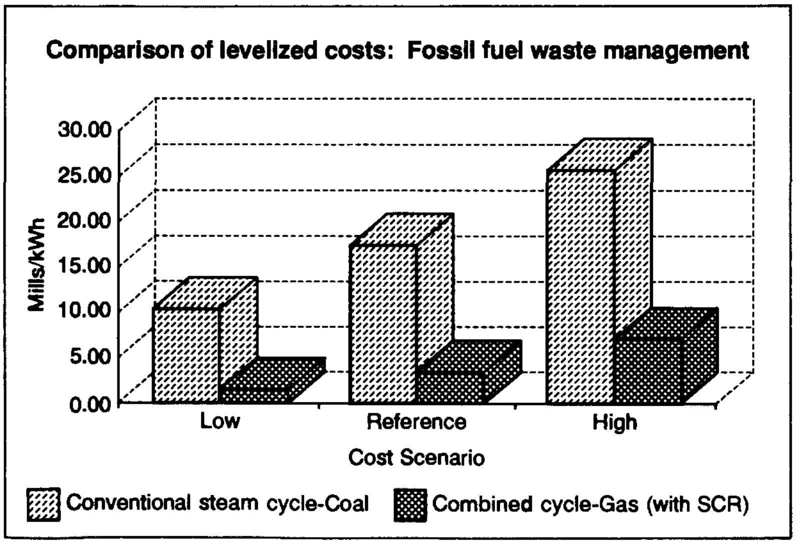
Mining and milling waste. All wastes arising from the milling of uranium ores are treated before any release takes place. The disposal of mill tailings is usually done on-site, often by covering the tailings to reduce radioactive dispersion.

Liquid wastes. Liquid waste treatment forms a significant part of the waste management scheme at most nuclear facilities. The waste management option depends on the characteristics of the waste and the quantity being produced. Small quantities of aqueous wastes containing short-lived radionuclides may be discharged into the environment. Liquid wastes containing large salt concentrations can be evaporated with the radioactive material being retained in the concentrate or being chemically precipitated to produce a sludge with suitable properties for further treatment. Some liquid wastes can be absorbed on solid matrices, again as a precursor to further treatment of the solid. Incineration is also sometimes used for volume reduction of active oils and combustible solvents. LLW and ILW concentrates are encapsulated in cement or bitumen matrices, and then packaged in suitable containers.

Liquid HLW from a reprocessing facility contains almost all of the fission products produced in the fuel. Currently such HLW is converted into glass using a vitrification process and the molten glass is cast into stainless steel containers prior to disposal in a suitable deep repository. (These high-level heat emitting wastes are classified as C1 in this assessment.)

Gaseous wastes. Radioactive gaseous wastes are usually discharged in the atmosphere in accordance with the appropriate regulatory requirement. Before discharge, the gaseous wastes are treated, if necessary, to ensure that the

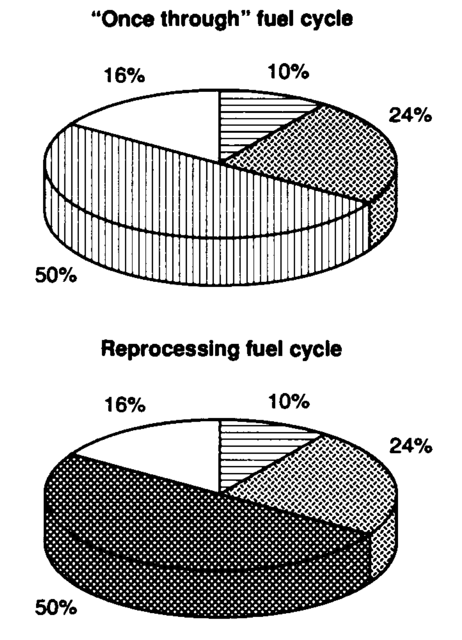




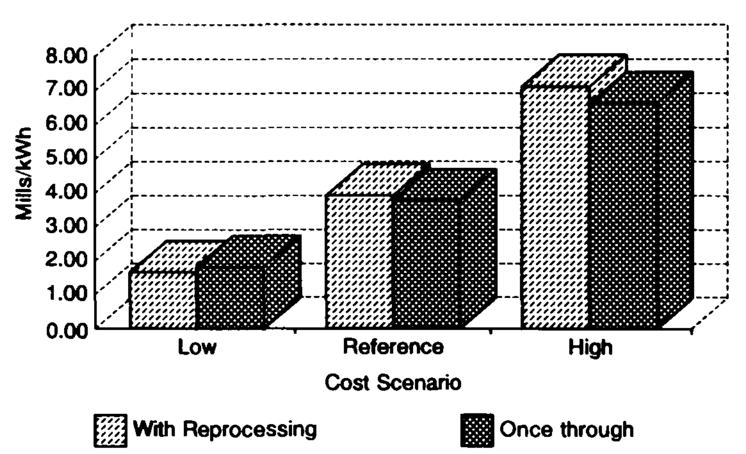
regulatory limits on the discharges are not exceeded.

Solid wastes. Apart from already mentioned vitrified reprocessing wastes, solid wastes also include cladding hulls and fuel assembly hardware (classified as C2), filters, used equipment, resins and sludges, scrubber solids, and general trash. All of the waste, except that with very low activity levels, will need some treatment and conditioning.

Treatment and conditioning operations include volume reduction, conversion of the waste to more stable forms, and packaging. The various stages of waste management for the PWR cycle considered here produce different volumes of conditioned solid wastes. *(See table, page 29.)*



Nuclear power waste management cost estimates



Comparison of levelized costs: Nuclear waste management

Disposal in a suitable facility, which may be deep geologic or near surface, contributes to limiting any transport of radionuclides into the environment to acceptable levels. For the once-through cycle, spent fuel is stored for a period of years, probably several decades to allow the radioactivity and associated heat load to decay before disposal.

Methodology for cost assessment

The data for each of the cost components of waste management have been obtained from a survey of existing estimates. In order to provide a basis for a meaningful comparison of costs, the raw data have been adjusted where necessary and applied to the reference cases. Finally, all cost estimates have been converted to a common basis of levelized unit energy (LUC) costs expressed in US dollars as of 1 July 1991, per kWh. The LUC is defined such that the present value of the cost stream equals the present value of the single value levelized cost times the number of units (kWh) in each timeframe. In order to put waste management costs on a common basis for comparison purposes, it is necessary to convert all cost flows to a common value by the procedure of discounting. This is widely accepted in economic assessments as a procedure which facilitates the comparison of investment options having distinct cash flows spread out in time.

The major criticism of applying the discounting technique to the assessment of the cost of nuclear power is its application to significant cost streams long after the production of electricity from the nuclear generating station ceases. This criticism relates to intergenerational equity — that is, the extent to which electricity customers pay the full costs of serving them and the extent to which future generations bear costs from which they receive no benefit.

In order to recognize this concern, the reference cases are based on a 5% real discount rate to the end of power plant life followed by a zero discount rate thereafter. A 5% real discount rate is favoured by many countries of the Organization for Economic Co-operation and Development (OECD). In addition, the results have been tested for sensitivity to different factors: the discount rate, the capacity factor, and the service life of the power plant.

Cost data

Fossil fuel cycle. For both fuel cycles the levelized waste management costs cover a range of about 0.5 to 2.0 times the reference cases. *(See graphs.)*

When looking at the relative proportions of these costs, the control of SO_2 alone contributes about 48% of the costs in the conventional steam cycle coal plant. For the combined cycle, 99% of the waste management costs are comprised of the decommissioning cost.

Fossil fuel waste management costs are in the range of close to zero to about 25 mills per kWh (a mill is one-thousandth of a US dollar). The costs are expected to remain in this range with typical variations in capacity factor discount rate or service life. The low end of the range corresponds to gas-fired generation and the high end to coal-fired generation. At these levels, waste management costs represent a low to moderate fraction of the overall cost of baseload electricity generation from fossil fuels. Total levelized costs of fossil-based electricity generally fall in the range of 40-60 mills per kWh.

Nuclear fuel cycle. The levelized cost of waste management for the two nuclear fuel cycles assessed are similar. *(See graphs.)*

For both cycles, waste management at the front end of the cycle leads to about 10% of the total waste management cost. Of this, about one-third is due to the management of depleted uranium as a waste. The management of wastes from power plant operation accounts for about 24% of the costs and 15% is due to power plant decommissioning. The remaining 50% of costs is associated with the back end of the fuel cycle.

Nuclear waste management costs are in the range of 1.6 mills/kWh to 7.1 mill/kWh. As in the case of fossil waste management, such costs represent a low to moderate fraction of the cost of electricity generated. The waste management costs may be compared to the cost of nuclear powered electricity, which is 30 to 50 mills/kWh.

Comparison. The waste management costs for the nuclear cases lie between those of the two fossil cases. They are closest to the costs for gas-fuelled combined cycle, which represents the lower end of the fossil range. The coal-fuelled option, representing the top end of the fossil range, has waste management costs which are about a factor of four above those of the nuclear cases.

While both the nuclear cases show a range between the high and low values covering a factor of four, the variability in fossil cost estimates only cover a factor of two or less. This difference in variability can in part be attributed to the fact that the fossil costs are based on established technology, while the nuclear costs include a substantial contribution from waste management activities which have yet to be firmly established. Even though flue gas treatment is a relatively new field, several plants are in operation and the cost estimates are firmer than those for some nuclear waste management techniques, such as decommissioning and deep repositories. In light of this, there is greater uncertainty associated with nuclear waste management costs than with those fossil waste management activities considered in this assessment. Some of the difference in variability between fossil and nuclear waste management cost estimates is also due to the effect of differences between local conditions, including regulatory requirements.

Possible future changes

For nuclear generation a major shift in waste management practices or expectations is not foreseen. Nonetheless the future holds some possibilities that could influence waste management costs. These include attempts to increase fuel burn-up, better housekeeping, and more effective and advanced waste treatment techniques, such as supercompaction, biodegradation, incineration, and plasma torch burning. All of these developments hold the promise of reducing nuclear waste management costs. The future will also bring the development of deep repositories and much greater experience with decommissioning. While these bring with them the risk that costs might turn out to be higher than expected, they will also significantly reduce the uncertainty with respect to nuclear waste management costs.

In the case of fossil waste management costs, one of the major developments is expected to be the more widespread use of clean coal technologies. This will result in reduced environmental impacts and waste management costs through a technology that better integrates emission control within the power generation process itself. A further possible development related to fossil-fuelled generation is regulation with respect to CO_2. This could involve the development of technological solutions such as the disposal of CO_2 in empty gas fields at the bottom of the ocean, or the introduction of carbon taxes — both of which could significantly increase fossil waste management costs.

For both nuclear and fossil cases, there is also the possibility that existing waste management regulations will be further tightened. This would include the possibility that residual environmental costs would have to be internalized by electric utilities. Such changes would bring with them increased costs. ❐