Nuclear uncertainties

Energy loans for fission power

Jan Willem Storm van Leeuwen

The energy requirements and costs of the complete nuclear fuel cycle of a light water reactor (LWR) power plant are analysed, from mining the uranium ore to dismantling the nuclear facilities and final disposal of the radioactive wastes. The most critical parameters are identified and discussed. The analysis has an empirical character: only data which are supported by practice are used. The conclusions differ significantly from previous studies, mainly because of the complete approach and the use of recent figures and trends.

Keywords: Nuclear power; Fission; Energy loans

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[1]P.F. Chapman, 'Energy analysis of nuclear power stations', *Energy Policy*, Vol 3, No 4, December 1975, pp 285–298.
[2]W.D. Franklin, M. Mutsakis and R.G. Ort, *Total Energy Analysis of Nuclear and Fossil Fueled Power Plants*, ORNL–MIT–138, Oak Ridge, TN, USA, 23 November 1971.

Long-term cost calculations, over 20–30 years or more, are subject to large uncertainties. In fact they have little, if any, practical value. This is particularly true in the case of nuclear energy, for the following reasons:

- There has only been limited experience of nuclear power. A few reactors have reached a lifetime of 20 years but on a larger scale the operational experience covers a period of about ten years.
- The end of the nuclear fuel cycle – reprocessing of spent fuel, dismantling of nuclear facilities, treatment and final disposal of all kinds of nuclear wastes – is still in an experimental or preoperational stage.
- A nuclear project takes 50–170 years to complete (see Figure 1).

Obviously large uncertainties are introduced in each of these factors. Costing a project 170 years ahead is at best a very rough approximation. The great time span is an unfamiliar phenomenon in economics.

A more reliable way to tackle the problem is to assess the activities, energy and materials required to complete the project. The requirements of all activities related to a particular nuclear power plant are imputed to that project, whenever and wherever these activities will take place. Such an approach allows an examination of the viability of a given project with the present state of technology. Energy analysis may help to identify possible technological advances in one or more sub-processes necessary to make the complete system viable from an energy point of view. If such advances are needed, continuation of the system means acquiring an energy debt, to be repaid in the future. Furthermore, long-term environmental effects of any technology can be assessed more easily, starting from an energy analysis.

This energy analysis differ from Chapman's[1] and other studies,[2–9] mainly in the following respects:

- The physical losses of the chemical processes in the nuclear fuel cycle, eg the milling of low-grade uranium ores, are included.
- Consumption of materials and energy is computed for the lifetime of the reactor and its associated facilities, and not per tonne of uranium.
- Total electricity production is calculated over the lifetime of the

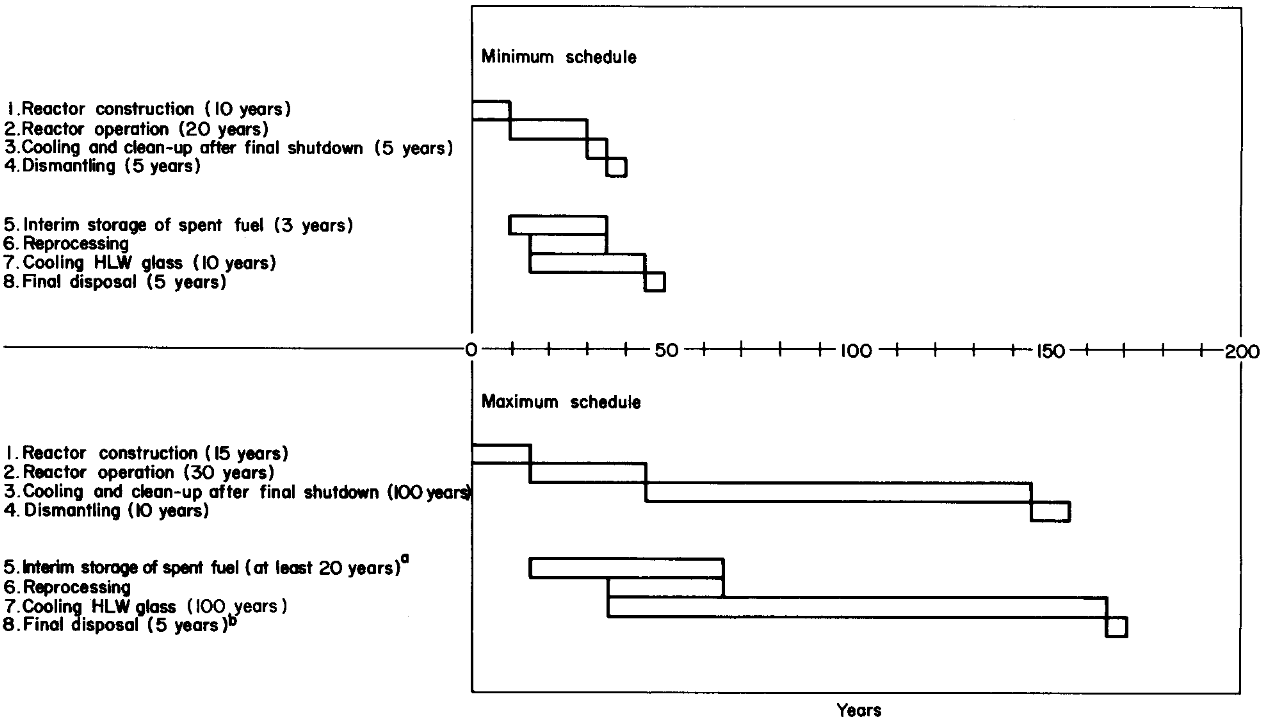

Figure 1. Schedules for a nuclear fuel cycle with a light water reactor.

[a]At the moment this time span is indefinite but at least 20 years, because of lack of reprocessing capacity. This situation will continue at least 10–20 years, in view of the large amounts of stored spent fuel and the low construction rate of new capacity.
[b]This figure includes mining and sealing of the repository.
In view of the present situation in the nuclear industry (eg backlog of reprocessing capacity), the shortest attainable schedule is currently 70–80 years.

plant, as a function of the productive lifetime, which is measured in full-load years. Lifetime and load factor are not independent. The use of full-load years avoids discussions about the most probable load factor and lifetime.

- The back end of the nuclear fuel cycle is included, ie, interim storage of spent fuel and other wastes, reprocessing of spent fuel, vitrification of high-level wastes, solidification and packaging of other radioactive wastes, including decommissioning wastes, dismantling the nuclear power plant and the reprocessing plant, transport and final disposal of all wastes, including dismantling wastes, into a geological repository (eg salt mine).
- A distinction is made between the European and US situation, because of the much higher specific energy use of the US economy, compared to the European economies.

Apart from these differences, a revised analysis was necessary because of rapidly escalating costs and use of materials, energy and manpower in construction of nuclear power plants and reprocessing plants, during the past ten years. An increased database has also become available on waste management and final disposal.

The energy requirements of the nuclear fuel cycle are calculated as much as possible from empirical data. In cases where little or no experience exists, estimates are made based on empirical data from related processes. Requirements for treatment of the mill tailings of uranium mines are not included, because of insufficient data. Radioactive waste conditioning is assumed to be carried out according to the present views in the nuclear industry.

[3]*Energy Study: Interim Report 26 July 1974*, Oregon Office of Energy Research and Planning, Salem, Oregon, July 1974.
[4]Ch.T. Rombough and B.V. Koen, *The Total Energy Investment in Nuclear Power Plants*, Technical Report ESL–31, Energy Systems Laboratories, College of Engineering, The University of Texas at Austin, November 1974.
[5]Stanford Research Institute, *Manpower, Materials, Equipment, and Utilities Required to Operate and Maintain Energy Facilities*, Bechtel Corporation, March 1975, NTIS: PB–225 438.
[6]R.M. Rotty, A.M. Perry and D.B. Reister, *Net Energy From Nuclear Power*, Report IEA–75–3, Institute for Energy Analysis, Oak Ridge Associated Universities, November 1975.
[7]J. Kistemaker, *Energie–analyse van de totale kernenergie cyclus gebaseerd op licht water reactoren (Energy analysis of the complete nuclear fuel cycle based on light-water reactors)*, LSEO 682, FOM Instituut voor Atoom- en Molekuulfysica, Amsterdam, summer 1975 (in Dutch).
[8]G. Kolb, F. Niehaus, St. Rath-Nagel and A. Voss, *Der Energieaufwand für den Bau und Betrieb von Kernkratwerken*, Kernforschungsanlage Jülich (KFA), Jül–1230, August 1975.
[9]N.D. Mortimer, *The Energy Analysis of Burner Reactor Power Systems*, thesis, Open University, Milton Keynes, December 1977.

Important factors

The reference reactor is a pressurized water reactor (PWR) of 1 GWe, since at present about 60% of all operating power reactors in the world are PWRs, a percentage which is still growing. It is generally agreed that the light water reactor (LWR) is an interim phase in the development of nuclear energy until the LMFBR (liquid-metal cooled fast breeder reactor) comes on line.

The reprocessing stage can be dispensed with in the so-called 'once-through cycle'. In that case the spent fuel is packed in protective containers, allowing it to be stored permanently in a safe place. Since this is generally considered to be an unrealistic option, few studies have compared the costs of the fuel cycle with and without reprocessing. Therefore, in this study, the once-through fuel cycle has not been considered.

Recycling the plutonium from the spent fuel into LWRs is theoretically possible, but this is fraught with technical and other problems. The costs of mixed-oxide fuel, in which plutonium replaces the fissible U–235, are several times, perhaps 10 times, the costs of conventional enriched fuel. At present plutonium recycling is not practised, except for a few experiments with a small number of fuel elements. Therefore, plutonium recycling has not been included in this study.

The energy content (energy credit) of the processed plutonium and uranium has not been accounted for, which is the same case for the energy content of the natural uranium. Only flows of fossil fuels and electricity are included in the present analysis. Moreover, the energy credit of the plutonium will be more than compensated for by its storage costs and energy requirements.

The processes in the nuclear fuel cycle preceding the actual reactor operation (the 'head' of the fuel cycle) are well established. Sufficient empirical data are available to allow a reliable energy analysis of this part. The tail of the fuel cycle, however, forms essentially a *terra incognita*: the processes involved are still in an experimental or pre-operational stage, so no operational data are available.

The following are the important phases in the energy and material requirements of the nuclear fuel cycle (see Figures 6 and 7):

- uranium mining and milling at low ore grades;
- construction of the nuclear power plant;
- reprocessing of the spent fuel; and
- dismantling the reactor and the reprocessing plant.

The first two processes are well known but their large energy requirements merit closer examination. The costs and energy requirements of the last two processes have to be estimated. The uncertain but possibly expensive nature of these two processes also merit further discussion. Another energy-consuming process is the transport and distribution of the electricity produced, but as this is not specific to a nuclear system, it is not discussed here.

The operating life of a nuclear power plant, a basic factor in the viability of the system, is determined by its technical life and the average load factor. These two parameters are dependent on each other (Van Waas[10]). In this study the operating life is defined as the product of life and load factor, measured in so-called 'full-load years'. A life of 20 years with an average load factor of 0.60 means an operating life $L_{100} = 20 \times 0.60 = 12$ full-load years.

[10]Th.J. Van Waas, *De prijs van atoomstroom, een slag in de lucht*, report to the Stuurgroep Maatschappelijke Discussie Energiebeleid, Den Haag, Netherlands, 29 July 1982.

The statistical study of Van Waas shows that an operating life of about 10 full-load years can be considered as the most probable for the present LWRs and he did not detect any increasing or decreasing trend in this figure. In the present study a slightly optimistic operating life of L_{100} = 12 full-load years has been used as the reference case. The energy requirements of the fuel cycle are calculated as a function of the operating life.

Uranium mining and milling

Figure 2 shows the energy requirements of mining and milling as a function of ore grade. Curve 'a' represents the mining and milling technique used for rich ores: G = 0.1% U_3O_8 or higher, eg the US sandstones. Curve 'b' represents the technique used for lean ores, such as the South African ores. The dashed line 'c' represents the energy requirements for lean ores, found by extrapolating the curve for rich ores, without taking into account the extraction losses. The horizontal line marked by $3J_3$ represents the total gross electricity production of the reference reactor during an operating life of L_{100} = 12 full-load years, converted into fossil fuel equivalents. During this period the reactor consumes 2815 tonnes natural uranium. The shaded band represents the net energy production, averaged over the European and US situations, taking into account only the head of the nuclear fuel cycle. If the tail, comprising reprocessing, dismantling the reactor and reprocessing plant, waste conditioning and final disposal, is also taken into account, the net energy production can reach negative values.

As can be seen from Figure 2, ignoring the extraction losses in the milling process leads to underestimation of the energy requirements of

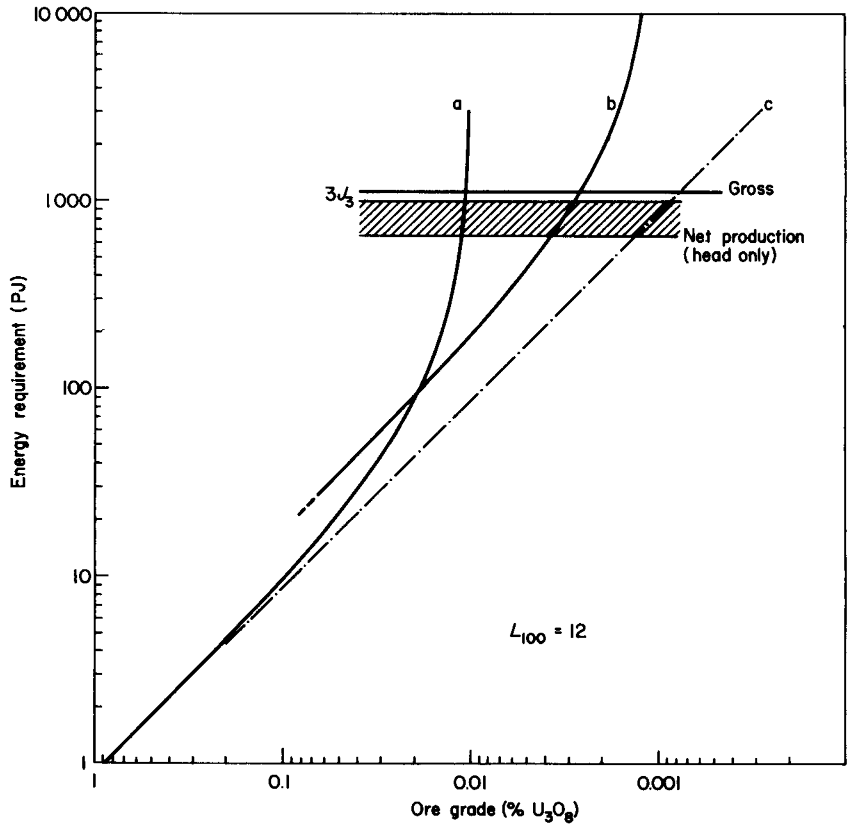

Figure 2. Energy requirements, Q, of mining and milling of 2815 tonnes of natural uranium as function of ore grade, G.

Q = sum of the thermal inputs (J_1) and electrical inputs (J_2), with electrical inputs converted into fossil fuel equivalents: $Q = J_1 + 3J_2$.

the process. From Figure 2 several lower limits of mineable ore grades can be deduced. If no extraction losses and no energy requirements of the nuclear fuel cycle are taken into account, an ore grade of 8 ppm seems to be the minimum. At this ore grade the mining and milling alone will consume as much energy as can be produced from the uranium in the ore. This extrapolation, line 'c' in Figure 2, has been used in other energy analyses.

If the extraction losses are taken into account, a minimum of about 26 ppm appears possible. If the additional energy requirements of the head of the nuclear fuel cycle are taken into account, the cutoff grade rises to 30–40 ppm U_3O_8. In practice the cutoff grade will be much higher, because the tail of the fuel cycle also consumes a considerable amount of energy. This suggests a new viewpoint from which the uranium resources of the world should be assessed. Deposits such as the Chattanooga shales, for instance, can no longer be considered uranium ores for LWRs.

The energy requirements of mining and milling appear to play no significant role in the complete nuclear fuel cycle at ore grades of G = 0.1% U_3O_8 or higher. So the results of the present study with G = 0.1% U_3O_8 are typical for all higher grades. At present this is the average grade for the ore mined in the USA. Below 0.1% U_3O_8 the ore grade becomes an increasingly important factor in the total energy requirements of the nuclear fuel cycle. In the present study lean ores are taken to be those with G = 0.01% U_3O_8.

From an environmental point of view it should be noted that, for a PWR with an operating life of 12 full-load years, 50 tonnes of mined uranium ore with an ore grade of 0.01% U_3O_8 are needed. This is equivalent to the amount of coal needed to produce the same quantity of electricity in a coal-fired station.

Construction

In Figure 3 the historical capital costs of nuclear power plants in the USA are given, including some estimates (circles, squares and triangles) from other authors. The costs show a marked minimum in 1970. After this the capital costs have risen steadily at a constant percentage per year (see Figure 4). Woite[11] estimated a rate of 28% annually, including inflation. Shaw[12] found an escalation rate of 16% annually, excluding inflation. Extrapolation of the figures of Woite and Shaw to 1982 results in a capital cost range of \$3100–5200/kWe. This closely matches the actual cost range of \$1200–5600/kWe of power plants under construction or put into operation in 1982. As long as the causes of the large divergence in the capital costs are unknown, it may be incorrect to consider it as a purely stochastic phenomenon and this study uses the full cost range.

Figure 4 shows little sign of a decreasing cost escalation rate, confirming the results of the study by Mooz.[13] One effect should be noted however, *viz* the cancellation of the most expensive nuclear power plants. This effectively puts a ceiling on capital costs which can be mistaken for a decreasing trend.

The statistical study of the US nuclear power plants by Mooz proved that there are no relations between capital costs and construction time, power rating of the reactor, or construction as twin stations. The only connection appeared to be between capital costs and the first year of

[11] G. Woite, 'Capital investment costs of nuclear power plants', *IAEA Bulletin*, Vol 20, No 1, February 1978, pp 11–23.
[12] K.R. Shaw, 'Capital cost escalation and the choice of power stations', *Energy Policy*, Vol 7, No 4, December 1979, pp 321–328.
[13] W.E. Mooz, 'Cost analysis for LWR power plants', *Energy*, Vol 6, 1981, pp 197–225.

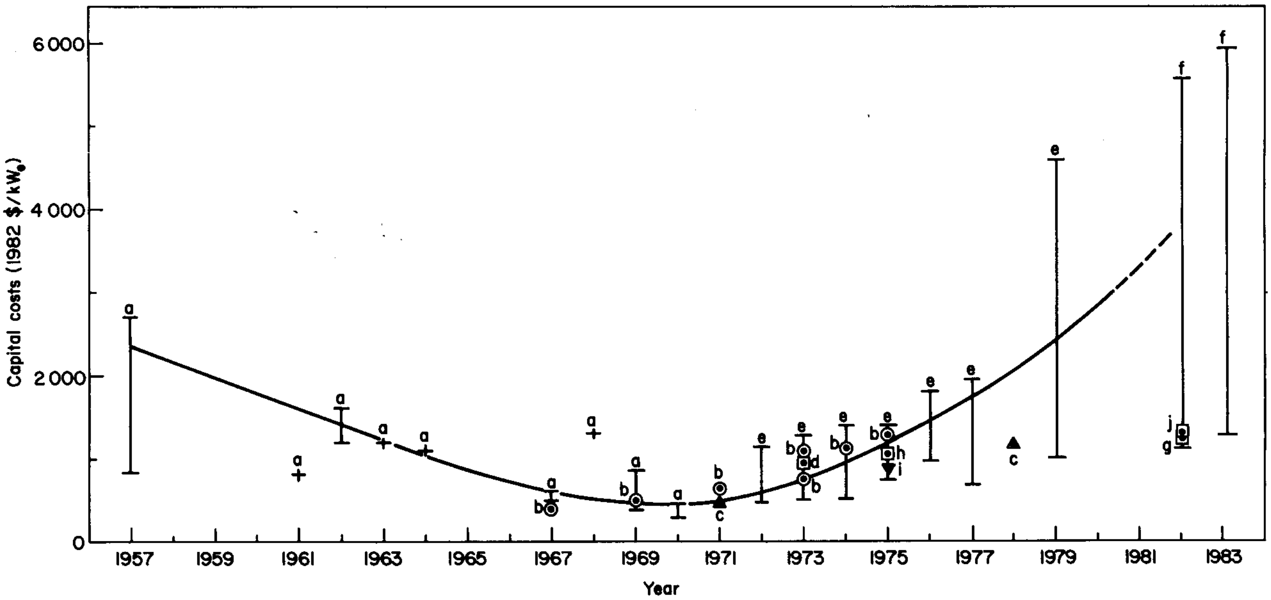

Figure 3. Specific capital costs of nuclear power plants, rated at 50 MWe (net) or more, in 1982 $/kWe by year of start of operation (linear scale).

(a) Actual costs observed in the USA by Roddis and Ward[27]; (b) cost estimates of US nuclear power plants from Woite[11]; (c) Komanoff[28]; (d) Oregon[3]; (e) Actual costs from the USA as listed by Mooz[13] by year of operation; (f) Actual costs from the USA of 30 plants under construction or coming on line in 1982 and 1983, quoted in *Nuclear News* and *Nuclear Engineering International*; (g) KIVI[29]; (h) Kistemaker[7]; (i) Manderbach[30]; (j) OECD[31].

construction. Paik and Schriver[14] claim to have found scale economies, using data from plants completed after 1979.

There are some notable aspects of Figures 3 and 4:

- The absence of a 'learning-by-doing' effect after 1970. The bulk of the commercial nuclear power plants have been commissioned since 1970. A decreasing or at least a levelling trend in the specific capital costs could have been expected.
- The large divergence in the capital costs. In 1982 the highest noted costs were five times the lowest. An explanation of this has yet to be found.

[14]S. Paik and W.R. Schriver, 'Effect of increased regulations on capital costs and manual labor requirements of nuclear power plants', *The Engineering Economist*, Vol 26, No 3, Spring 1981, pp 223–244. See also: *The Energy Daily*, 7 June 1982, p 2.

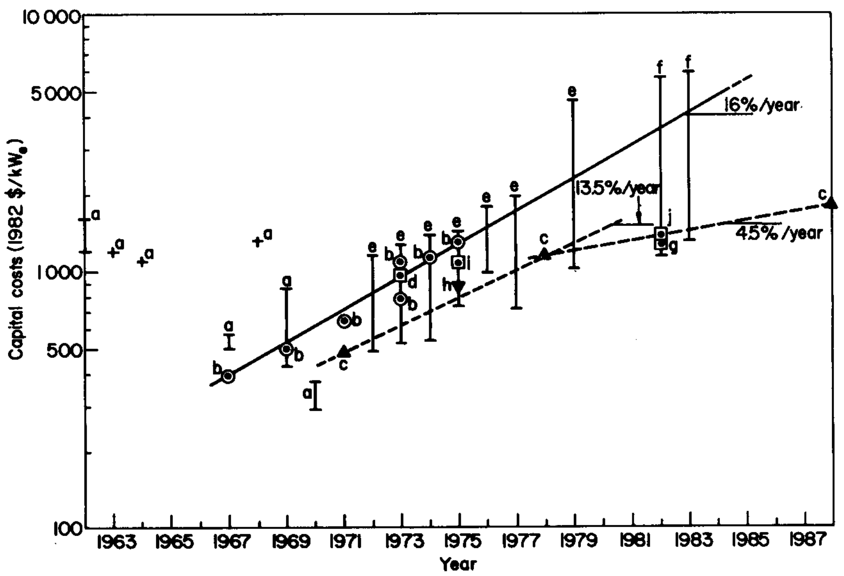

Figure 4. Specific capital costs of LWR power plants, rated at 50 MWe (net) or more, in 1982 $/kWe on semi-logarithmic scale.

See Figure 3 for key. The solid line represents a real cost escalation of 16% per year, as observed by Woite[11] and Shaw[12]. Komanoff apparently assumes a escalation rate of 13.5% per year until 1979, and 4.5% per year after 1979 (broken line).

In 1964 the Atomic Energy Commission (AEC, now US Department of Energy) expected a continuing decreasing trend in capital costs. For 1980 a cost of $125/kWe (in $1964, or $332/kWe in $1980) was forecast, based on the learning effect and scale economies (McLain[15]). The actual costs in 1980 were about ten times higher.

In previous studies the energy requirements of construction were based on the low capital costs of the early 1970s. Since the costs rose steeply to ten times this in 1982, a revised calculation of the energy requirements for construction has become necessary. The question arises whether the cost escalation is coupled with a similar escalation in energy requirements. The studies of Shaw,[12] Paik and Schriver,[14] Crowley and Griffith[16] and many others show that the complexity of nuclear power plants is continuously increasing both technically and organizationally. A strong correlation exists between escalating costs and escalating use of energy, materials and manpower. There is no reason to suppose a deviation from the findings of Rombough and Koen[4] and others (see Chapman[1]), that the construction of a nuclear power plant can be considered an average economic activity, within the same attainable accuracy from an energy point of view.

Three methods are available for determining the energy requirements for construction of nuclear power plants:

- An elaborate input–output analysis, for example, the study by Rombough and Koen, amongst others. It is inferred from their studies that an input–output analysis yields the same result as the next method.
- Multiplying the capital costs of nuclear power plant in a given year (here 1982) with the national energy/GDP coefficient of the same year. Since the cost figures are related to the US situation, the US energy/GDP ratio should be used.
- Using the correlation between specific financial value (in $/kg) of a good and its specific energy requirements (in J/kg), as has been shown by Roberts.[17]

The third method yields a slightly higher value than the second. Because of its somewhat higher reliability, the method is used in the present study. Building the same nuclear power plant in Europe would probably require about 50% less energy than in the USA, in view of the lower energy intensities of economic activities in Europe (Dunkerley[18]). In the present study only the US values are used.

Reprocessing

In Figure 5 the historic reprocessing costs are represented in $1982/kg. The points with circles represent prices based on actual reprocessing plants, those with squares represent estimates based on hypothetical plants. The bars represent cost ranges, dependent on assumed load factor. The escalation rate of the real costs is 50–60% per year, from 1973 up to 1983. Before 1973 the escalation rate was about 11% per year. Apart from the high escalation rate, other aspects of the diagram are noteworthy: the absence of a learning effect; and the large uncertainty range in the cost estimates. Reprocessing technology still appears to be an immature technology.

In the present study (1984) a cost range of 4000–10 000 $/kg (1982$) was calculated, independently of Figure 5. These costs include:

[15]S. McLain, 'Commercial power reactors cooled with gas or light water', *Reactor Technology, Selected Reviews 1964*, pp 1–69, USEAC Argonne National Laboratory, July 1964.
[16]J.H. Crowley and J.D. Griffith, 'US construction cost rise threatens nuclear option', *Nuclear Engineering International*, June 1982, pp 25–28.
[17]P.C. Roberts, 'Energy and value', *Energy Policy*, Vol 10, No 3, September 1982, pp 171–180.
[18]J. Dunkerley, *Trends in Energy Use in Industrial Societies. An Overview*, Research Paper R–19, Resources for the Future Inc, Washington, DC, 1980 (distributed by Johns Hopkins University Press, Baltimore, Maryland 21218).

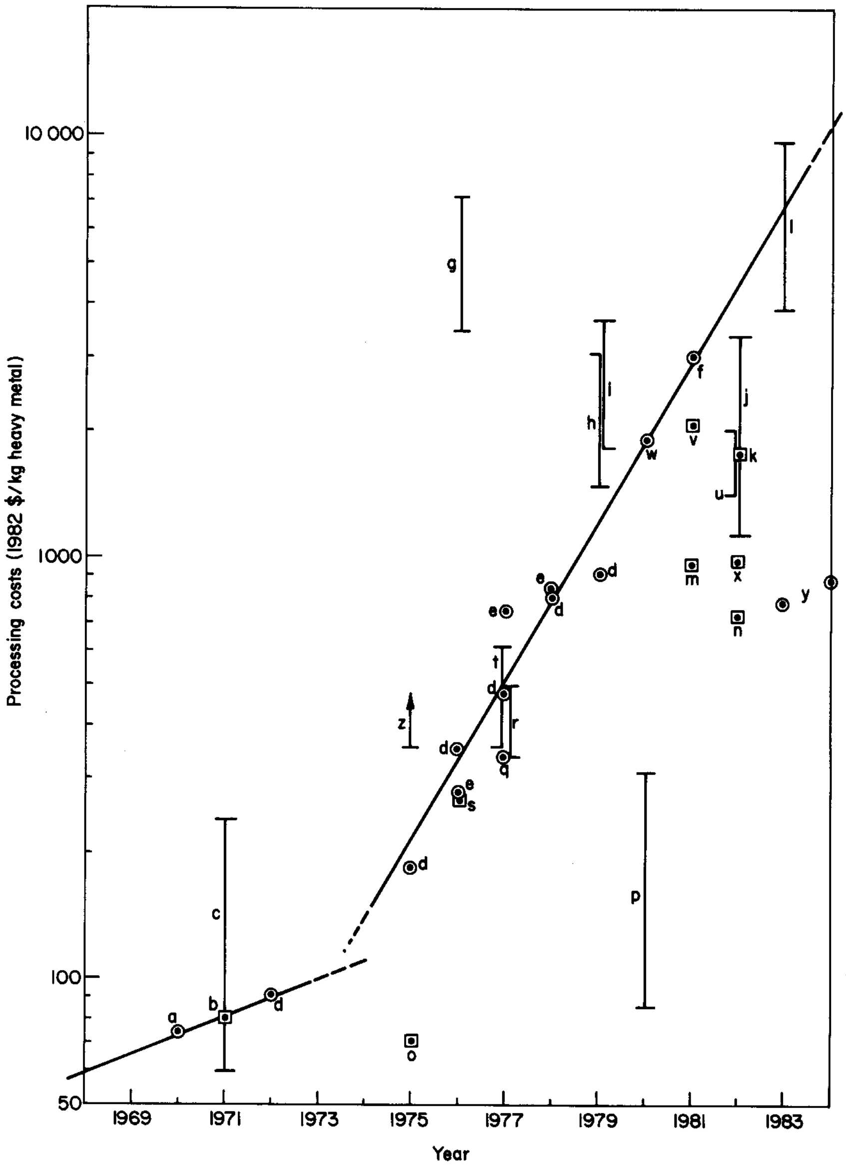

Figure 5. Historical costs of reprocessing, in 1982$/kg heavy metal.

Data were taken from the following references: (a) Ref 4; (b) Ref 32; (c) Ref 33; (d) Ref 34; (e) Ref 35; (f) *Atomwirtschaft*, December 1981, p 641; (g) Ref 36; (h) Ref 37; (i) Ref 38; (j) Ziegler, *Atomwirtschaft*, May 1982, p 254 (range caused by uncertainty in the meaning of his statement); (k) Ref 39; (l) this report; (m) Ref 40; (n) Ref 29; (o) Ref 7; (p) Ref 41; (q) *Time*, 2 May 1977, pp 6–11; (r) Ref 42; (s) Ref 43; (t) Ref 44; (u) Ref 45; (v) *Der Spiegel*, No 38, 1981; (w) *Atomwirtschaft*, February 1984, p 73; (x) B. Wolfe, *Nuclear Fuel*, 31 January 1983, p 12; (y) Cogema and BFNL official figures, without construction and escalation costs; (z) Ref 46; McLain[15] cites $74/kg (1982$) for NFS West Valley, and $16–19/kg (1982$) for a large hypothetical plant in 1962. These values are not shown in the graph.

- construction of the reprocessing plant;
- transport of the spent fuel from the reactor to the reprocessing plant;
- interim storage of the spent fuel before reprocessing;
- vitrification of the liquid high-level waste (HLW);
- conditioning of all other wastes originating from the reprocessing;
- interim storage of the vitrified HLW until permanent disposal is possible (about 50 years); and
- transport of all wastes to the final repository.

Decommissioning

No large power reactor or reprocessing plant has ever been dismantled. Decommissioning is the last but least-known phase of the nuclear fuel cycle. Until 1976 this inevitable tail activity had been largely ignored. Most studies on dismantling concluded that the costs will be about 10% of construction costs. A Swiss study[19] suggested about 20% of

[19]*Nucleonics Week*, 26 February 1981, pp 4–5.

construction costs. Another study, carried out by UNIPEDE in 1982 estimated 10–20% of the construction costs at constant price level.[20] A figure of 40% was mentioned at a recent conference.[21]

Dismantling a nuclear reactor comprises three stages:

- cleaning the reactor and other radioactive components;
- cutting the reactor vessel, radioactive components and biological shield into small pieces; and
- packing the radioactive debris and decontamination wastes for safe handling and for final disposal in a permanent repository.

In the present study only complete removal of the reactor is considered, because other options only postpone the last stage of decommissioning. No proof exists that entombed reactors can be 'stored' indefinitely on the surface, even in the deserts.

A cost range of 40–200% of the construction costs has been deduced. The official estimates of 10–20% are too low: maintaining the reactor during the post-shutdown period alone (ten years or more) will cost at least 5–10% of construction costs.

In the past, costs of new technologies, notably in the nuclear industry,

[20]*Nuclear Engineering International*, August 1982, pp 6–7.
[21]Commission of the European Communities, Conference on decommissioning of nuclear power plants, Luxembourg, 22–24 May 1984.

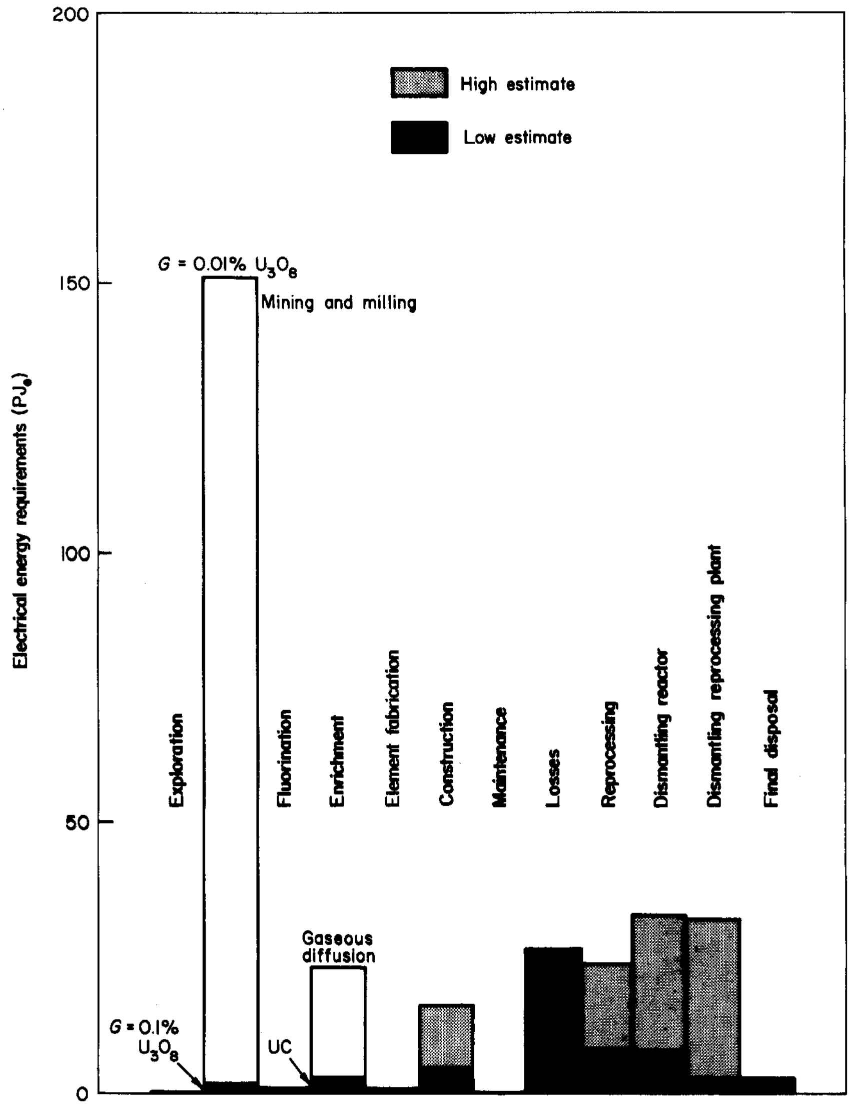

Figure 6. Electrical energy requirements, J_2, for the nuclear fuel cycle, with an operating life of L_{100} = 12 full-load years for the European situation.

Two ore grades, G = 0.1% U_3O_8 (typical rich ore) and G = 0.01% U_3O_8 (typical lean ore) are used. Enrichment by gaseous diffusion and ultracentrifuge (UC). Maintenance and internal use of electricity of the power plant are accounted for in energy production J_3. For the USA, the 'construction' column and the last four columns are twice as high as shown here.

have been systematically underestimated, often by a factor of 10 or more. Even projects using mature technology, such as construction of LWR power plants, are usually underestimated. Applying this empirical rule to the official appraisals produces a cost figure for dismantling of 100–200% or more of the construction costs. Until experience proves that dismantling costs are the sole exception to this rule, it seems prudent not to rely on the lowest possible estimates.

The cost range of 40–200% is not applied to the full range of construction costs. Statistically it seems improbable that a reactor with the highest capital costs also has the highest percentage dismantling costs. Hence the dismantling costs are based on the mean capital costs of \$2700/kWe. The same assumption holds for the energy requirements: 40–200% of the mean energy requirements for construction.

The costs of decommissioning Shippingport is estimated at \$60–70 million.[22] Shippingport has been built at a cost of \$72.9 million (1960\$), or about \$244 million (1983\$), so the dismantling costs, before the start of the project, are estimated to be about 29% of the construction costs. This estimate does not include cutting the reactor and other large components into small pieces, to be packed in standard waste

[22] *Nuclear Engineering International*, December 1983, pp 14–15.

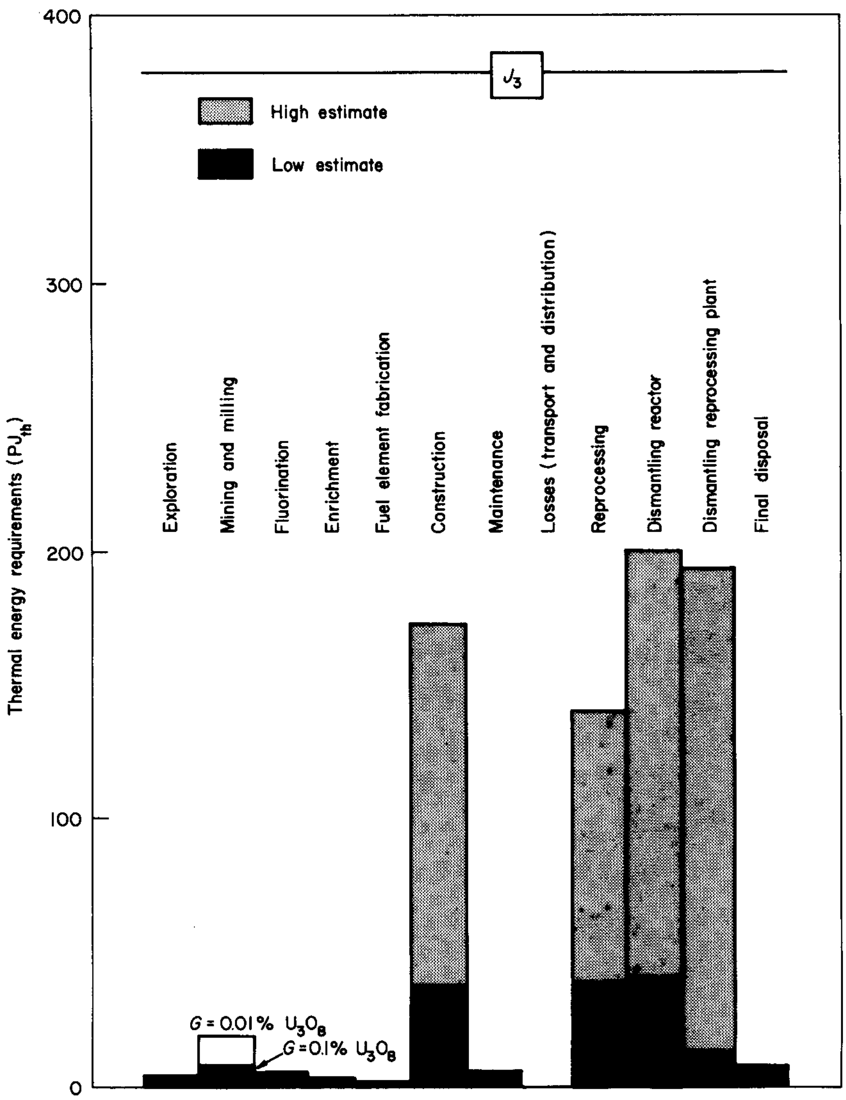

Figure 7. Thermal energy (fossil fuel) requirements, J_1, of the nuclear fuel cycle with an operating life of L_{100} = 12 full-load years, for the European situation.

Two ore grades, G = 0.1% and G = 0.01% U_3O_8 are shown. Enrichment by gaseous diffusion. Enrichment by ultracentrifuge has a slightly higher thermal energy input. J_3 = total net electricity production of the power plant alone, over 12 full-load years. For the USA the 'construction' column and the last four columns are twice as high as shown here.

containers. The costs of maintaining the reactor systems after shutdown prior to dismantling, of decontamination of the reactor systems and of packing the radioactive debris are also not included. The estimate of 12% of the construction costs[23] is not based on the original capital costs of Shippingport.

Studies of dismantling reprocessing facilities are even more scarce than for reactors. In 1977 two studies[24,25] assessed the costs at 45% or more of construction costs and BNFL's estimate in 1983 was 40%.[26] In the present study an estimate of 40–200% of construction costs and of energy requirements has been used. The energy requirements are reduced to energy units per kg processed fuel, in order to relate these requirements to the operating life of the reactor.

[23] *Nuclear Engineering International*, October 1984, p 23.

[24] H. Glauberman and W.J. Manion, *Technical and Economic Aspects of Nuclear Power Plant Decommissioning*, IAEA–CN–36/16, Int. Conf. Salzburg May 1977, IAEA, Vienna, Austria, 1977.

[25] K.J. Schneider and C.E. Jenkins, *Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant*, Battelle Pacific Northwest Laboratories, NUREG–0278, October 1977.

[26] *Nuclear Engineering International*, April 1983, p 11.

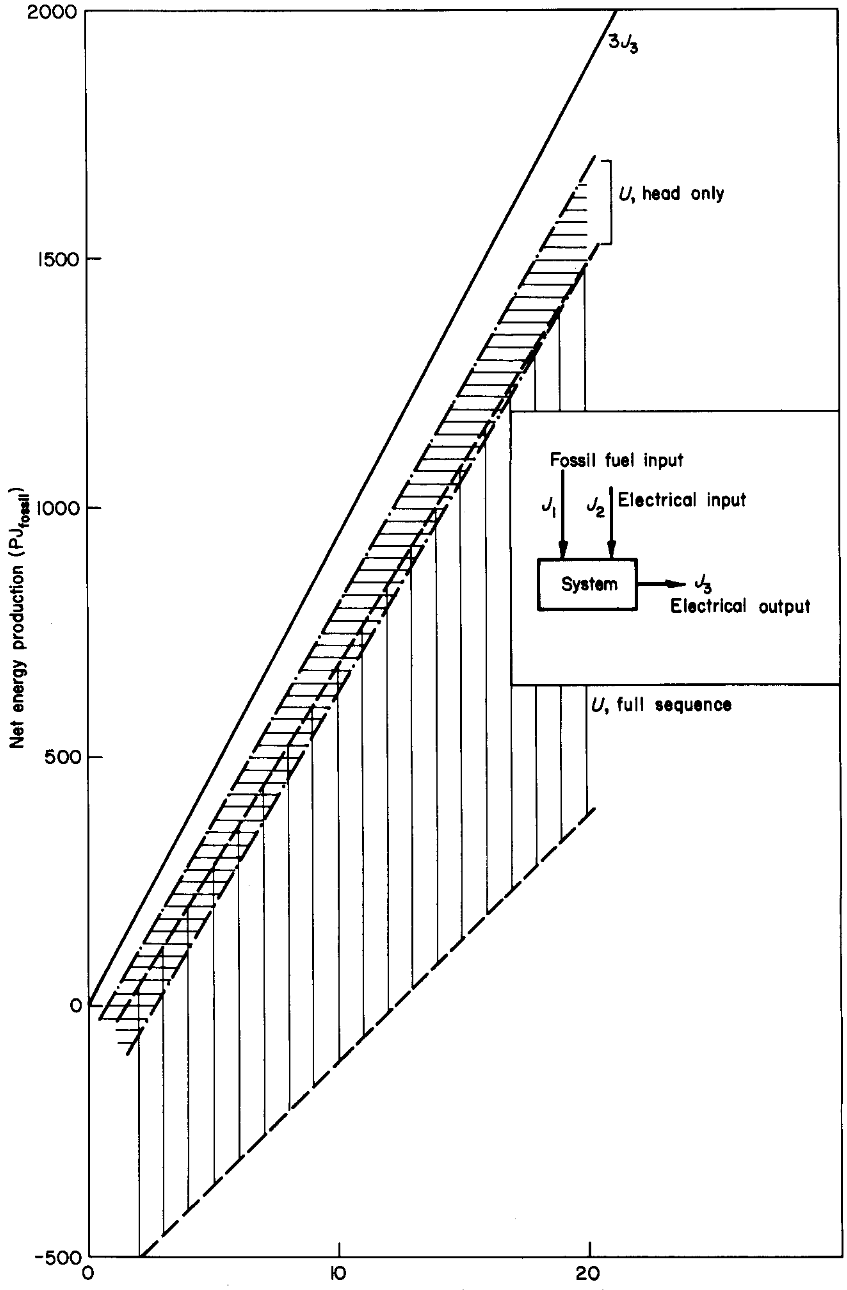

Figure 8. Net energy production, U, in petajoules (1 PJ = 10^{15} joule), of the complete PWR nuclear fuel cycle as a function of the operating life L_{100} in full-load years.

The European situation is shown, with G = 0.1% U_3O_8. $U = 3J_3 - J_1 - 3J_2$: the gross electricity production of the complete nuclear system minus the fossil fuel and electrical energy inputs, with all electrical energy flows converted into fossil fuel flows.

Results

The results of an energy analysis can be presented in various ways. In Figure 6 the electrical energy requirements of the nuclear fuel cycle in Europe are given, with an operating life of L_{100} = 12 full-load years, which is the base case in the study. Figure 7 gives the corresponding thermal energy balance.

Because of the complexity of the nuclear fuel cycle and of the energy supply system of a country as a whole, it is not possible to give one unambiguous definition of the efficiency of the nuclear system, which is useful in any situation. The nuclear system, however, should be compared with other energy systems, particularly the fossil fuel supply system. The motive for introducing nuclear power is generally to conserve and to replace oil or other fossil fuels.

To assess the oil-replacing efficiency of the nuclear system, one can use the net energy production U, measured in fossil fuel equivalents, as has been done in this study. The most favourable case is shown in Figure 8. The solid line represents the gross electricity production, converted into fossil fuel equivalents, $3J_3$, without taking into account the energy requirements of the fuel cycle outside of the reactor building. The vertical shaded area represents the possible values of U, taking into account the complete nuclear fuel cycle. The horizontal shaded area represents the possible range of U if only the head of the fuel cycle is taken into account. The intersection of the bands with the zero production level represents the energy payback times of the system. For the US situation and for lower ore grades, similar diagrams can be drawn. A convenient parameter is the energy payback time of the system, ie the time needed to produce the same amount of free usable energy (fossil fuel) as has been used to build and operate that system (see Figure 9). It should be noted that these results represent the present state of the art and any major breakthrough in technology could change this picture significantly.

Conclusions

The phases of the nuclear fuel cycle with the largest energy requirements and financial costs are:

- mining and milling of lean ores (ore grade G <0.1% U_3O_8);
- construction of the nuclear power plant;
- reprocessing of spent fuel; and
- dismantling the reactor and reprocessing plant.

Using uranium ores with grades G = 0.1% U_3O_8 or higher, the mining and milling process will have no significant effect on the energy efficiency of the nuclear fuel cycle. Below G = 0.1% U_3O_8 the proportion of mining and milling to the total energy requirements will increase rapidly.

Uranium deposits with grades G = 30–40 ppm U_3O_8 or lower cannot be considered as ores for a nuclear energy supply system based on light water reactors. The mining and milling alone would use as much energy as can be extracted from the uranium in these deposits by a LWR. In practice the minimal ore grade will be much higher because of the energy requirements of the rest of the nuclear fuel cycle.

Up to 1982 the real capital cost of LWR power plants rose at a rate of about 16% annually, from 1970 onwards. There are only weak signs, if

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any, of a flattening in the cost escalation. Reactor technology still has to be seen as an immature technology. Prognoses based on the assumption of a fully developed and mature technology, characterized by a learning effect, are consequently unreliable.

The real costs of reprocessing up to 1983 have risen at a rate of 50–60% annually. Reprocessing of oxide fuel with high burn-up from commercial power reactors must be considered to be a very immature technology.

The costs of dismantling nuclear facilities have to be estimated, as there is no current experience. The official estimates of 10–20% of the construction costs are too low. Some empirical data on related activities indicate possible costs of 20–200% of the construction costs. These indications have not been taken into account in the official studies.

From the beginning of nuclear technology in 1942 up to the present, the tail of the nuclear fuel cycle has been the subject of very little

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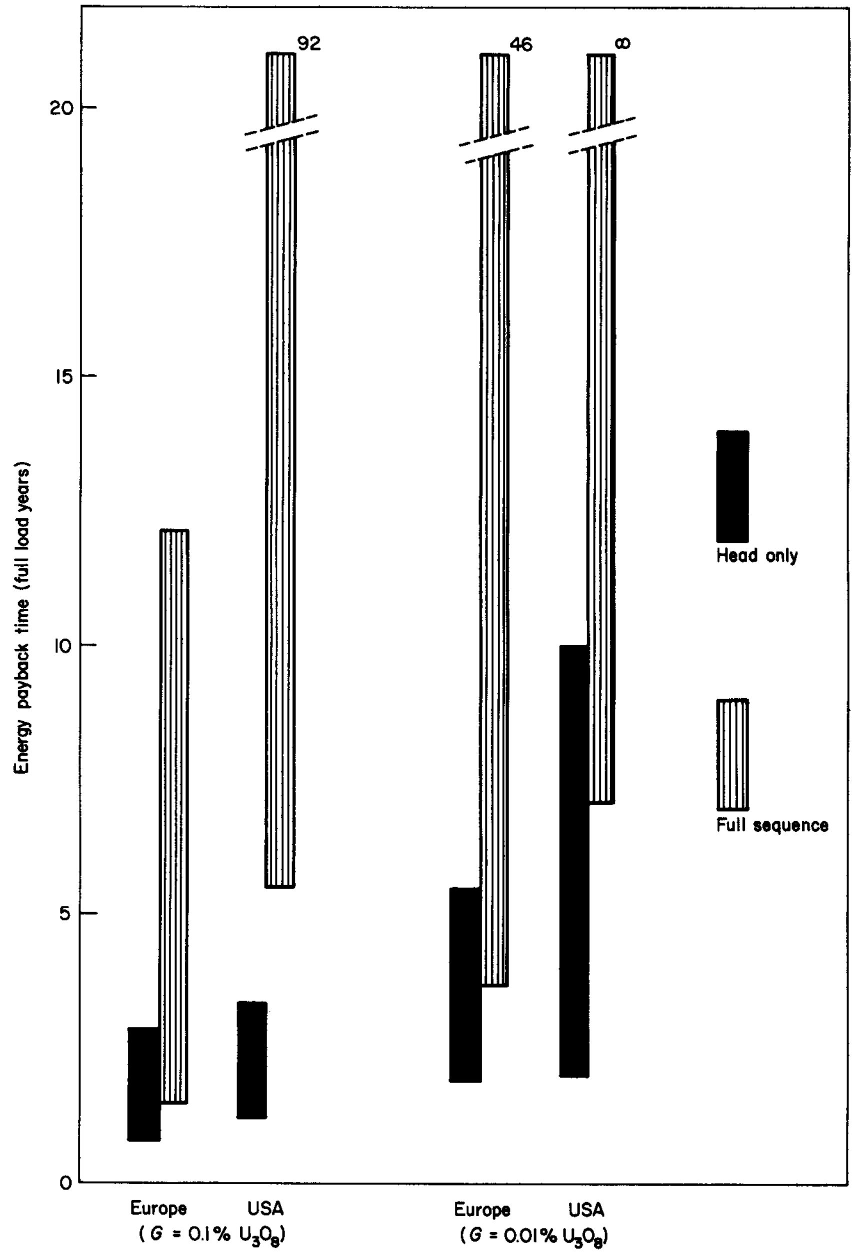

Figure 9. Energy payback times for European and US situations, with typical rich ores ($G = 0.1\%\ U_3O_8$) and lean ores ($G = 0.01\%\ U_3O_8$).

An operating life of L_{100} = 20 full-load years can be considered as a maximum: it means a technical life of 30 calendar years with an average load factor of 0.67.

research and development effort, compared with other processes in the nuclear fuel cycle. Waste treatment and dismantling have been, and are still being, pushed to the future. The costs of these future activities should be accounted for in the costs of nuclear electricity today, when comparing fission power with fossil power.

The uncertainties of the nuclear fuel cycle are such that no well-founded verdict can be given on the viability of fission power. Starting with the most optimistic assumptions, which are not supported by present practice, one can conclude that fission power will make a real contribution to the world's energy supply. Starting from less favourable assumptions, which are based on present practice, fission power will use more fossil fuel or other energy sources than it is supposed to be replacing. In view of the fact that the most optimistic goals in nuclear technology are seldom met, a careful approach to fission power economics is recommended.

To make fission power a safe and reliable energy source, which can compete with fossil fuels in the long term, significant breakthroughs, technically and organizationally, are needed in the following areas:

- construction of reactors and reprocessing plants;
- reprocessing of spent fuel;
- dismantling reactors and reprocessing plants; and
- waste treatment for final disposal.

With the present state of technology, application of fission power means contracting an energy loan for the very long term, 50–170 years. The energy produced by nuclear power plants now would need to be repaid later, to counteract the unwanted consequences of that nuclear power production.

The energy efficiency and economic viability of an energy supply system based on light water reactors is very sensitive to the operating life of the reactor and the reprocessing plant. The possible cost range for nuclear electricity is very wide. Even ignoring the uncertain but probably high costs of the tail of the nuclear fuel cycle, it seems doubtful whether the nuclear system will be a viable energy supplier.

The uncertainty in the range of costs and energy requirements for future activities in the tail of the nuclear fuel cycle, and even for present activities, are such that no justifiable prognoses can be made on the viability of fission power in the long term. Ignoring or underestimating the tail activities introduces a high economic and environmental risk. Eliminating the tail activities and proceeding with the once-through cycle only is being suggested as a viable option. However, dismantling the reactor and conditioning the spent fuel for final disposal are unavoidable activities. A dangerous approach to the problems of the tail activities would be to choose the least expensive solutions, regardless of safety and environmental aspects.