Annex F

ELEMENTS OF COSTS

1. Cost assessment of the fuel cycle with partitioning and transmutation

In the European Union strategy study [1], the main objectives were to analyse the potentialities of a strategy for managing radioactive waste aiming at reducing the inventory of long-lived radionuclides by P&T, and to assess its technological requirements and costs.

Before summarising the main conclusions of the economical impact of P&T on the overall fuel cycle, it is necessary to recall the scenarios defined in this study: three reference scenarios without and with standard reprocessing and three scenarios using P&T. They last 100 years as from 2000 to 2100 with a reactor park producing an average power of 120 GWe, which is close to the present situation in either Europe or the US.

1.1 Reference and P&T scenarios

Three reference scenarios were assumed:

- R1: open cycle with PWRs;
- R2: plutonium is recycled as MOX fuel in PWRs with conventional reprocessing;
- R3: similar to R2 until 2020; fast reactors (FR) of 1 500 MWe are progressively installedafter 2020.

The P&T scenarios were:

- RP1-1: transmutation of Np and Am in PWRs after 2010;
- RP1-2: transmutation of Np and Am in FRs after 2020;
- RP2: transmutation of Np, Am, Tc and I in CAPRA type FRs after 2030.

The characteristics of these scenarios were described in Section 3.2.1.1 of Part II.

1.2 Cost assessment

The cost supplement for implementing the RP1 enhanced reprocessing scenarios was assessed for each step of the fuel cycle: ore mining, conversion, uranium enrichment, fuel fabrication and reprocessing. The reactors and their operating modes are assumed to be identical for the standard and enhanced reprocessing scenarios, and there is no additional cost for reactor operation. Similarly, the quantities and activity levels of the waste destined for final disposal remain roughly the same in all scenarios, and the disposal cost is assumed to be unaffected.

For the other steps, fuel fabrication and reprocessing, the cost figures are either the current commercial ones or are extrapolated from those of similar existing facilities. Uncertainty margins are also calculated for the extrapolations. For reprocessing, a unit cost per metric ton of fuel is deduced from the assumptions concerning the operation and lifetime of the facilities (construction, maintenance, shutdown and decommissioning). The unit cost is specified in terms of the total adjusted cost for the throughput, with a 5% adjustment rate. The unit cost of fuel fabrication is estimated directly from current MOX fuel fabrication costs.

The unit costs defined above and the annual inventories are used to calculate the annual fuel cycle costs over the whole duration of the scenario. The sum of the annual costs yields an overall figure for each scenario.

The annual cost increase of the overall fuel cycle for the RP1-1 scenario with respect to R2 is estimated to be 33% with an uncertainty margin of 21% to 54%, when the costs have reached a steady state after 2070. Reprocessing (+15%) and minor actinide fuel fabrication (+17%) are the most significant additional expenditures, the costs of mining, conversion, enrichment, UO_2 and MOX fuel fabrication and waste disposal being similar in both scenarios. The relative weight of the different items in the cost breakdown of the fuel cycle is much the same for both scenarios, except for the relative cost of fuel fabrication (14% for R2 and 20% for RP1-1). Reprocessing is the dominant item with 45% of the total cost.

The annual cost supplement for the overall fuel cycle for the RP1-2 scenario compared with R3 is found to be 28% with an uncertainty margin of 11% to 52%, when the cost ratio has reached a steady state after 2070. The costs are still decreasing after 2070 for both scenarios, because FRs are replacing PWRs in the reactor park and the fuel cycle is cheaper for FRs than for PWRs. The main cause of the additional cost is enhanced reprocessing (+12% for PWR fuel and +14% for FR fuel). There is an increase in the relative cost of reprocessing from 59% for R3 to 66% for RP1-2, but the remaining items in the cost breakdown of the fuel cycle have the same relative weight in both scenarios.

Although no economic assessment was performed for the RP2 scenario because of the lack of precise specifications on the processes and facilities, the construction cost of an enhanced fuel and target reprocessing plant was estimated. Considering the technological improvements in the facilities and more effective waste management practices, the construction cost of this plant can be broken down into 68% for standard fuel reprocessing and U and Pu separation and 32% for target reprocessing and Np, Am, Cm, Tc and I separation. The additional cost for the construction of the enhanced reprocessing plant thus represents about 50% of the cost of standard reprocessing plants.

All these estimates are based on preliminary plant design sketches, and assume that ongoing process development work is successful. For the future plants that will be built during the next century, technological progress – some of which may be imagined today – may also significantly modify the cost of reprocessing and partitioning. Under these conditions, the estimates put forth here must be considered as merely indicative.

1.3 Summary of the European Union study

Compared to uranium and plutonium recycling only, the additional recycling of 95% of americium and neptunium increases the global cost of the overall fuel cycle by 10% to 50%. This increase mainly reflects the larger reprocessing and minor actinide fuel fabrication costs for the P&T scenarios.

2. Accelerator-driven system

The economics of the accelerator driven system depend on two main negative factors: the necessity to spend a part of the energy for the generation of a high-intensity proton beam and the capital cost of an accelerator. Cost estimations have been made for the LANL ATW and CERN EA facilities. Cost of licensing was not included in any of the estimates.

The LANL group estimated the total cost of a 3 000-MWt ATW facility to be about $2 500 millions [2,3]. The gross breakdown of the total cost is: accelerator (1 GeV-50 mA linac), turbines and other electrical equipment, $900 million; blanket, $300 millions; chemical plant, $500 millions; contingency and interest during construction, $800 millions. The 50-MW accelerator consumes 140 MWe, about 12% of total electric power (1 200 MWe).

Information on the cost estimates for the LANL system

ADS scenario: cost of accelerator (1 GeV, 40 mA) $500 millions, cost of subcritical burner (2 GWt) $750 millions, power conversion & distribution $750 millions. On top of them are costs for waste treatment, fuel fabrication and cleanup. The cost of these has only been estimated for a scenario of 20 ATW systems operating for 65 years. In this case this cost is $1 500 millions. The total capital cost for the full scenario is $41 500 millions.

The CERN group estimated the total cost for a prototype 1 500-MWt EA facility to be about $1 200 millions [4]. The breakdown of the total cost is; accelerator system (1 GeV-12.5 mA cyclotron), $180 millions; energy generating units, $60 millions; secondary loop and auxiliary systems, $70 millions; other direct costs, $480 millions; indirect costs, $400 millions. The power required to operate the 12.5 MW accelerator is 30 MWe, about 5% of total electric power (600 MWe).

3. Cost estimation of P-T for double-strata fuel cycle scheme

A cost analysis was carried out for P&T with the double-strata fuel cycle scheme based on the following conditions [5]. Since in dedicated transmutation systems, heavy neutron shielding and remote handling for fuel handling are needed due to high concentration of MA, very conservative (high) cost assumption was made for construction and operation of dedicated P&T facilities than those for commercial fuel cycle facilities.

- Performance characteristics of P-T:
  1. Partitioning: aqueous process for high-level liquid waste(HLLW) from PUREX reprocessing
  2. Transmutation:

System	1 000 MWt-ADS with a proton linac (1 GeV – 50 mA)
Subcritical Core	$k_{eff} = 0.95$
MA inventory	3 000 kg
MA incineration (fission)	
Amount	300 kg/year (the amount generated in 12 LWRs)
Rate	10%/year
Electricity generated by ADS	340 MWe
to accelerator	100 MWe
to grid	230 MWe

- Assumption for cost estimation:
  - Partitioning cost per kg of MA and FP: 5 times higher than that of PUREX reprocessing;
  - ADS fuel processing cost: triple of that in LWR fuel cycle;
  - Construction cost per MWt of an ADS: 1.5 times of that of LWR;
  - Construction cost of the accelerator: 50 B yen;
  - Capital cost is proportional to construction cost;
  - Operation cost of 1000 MWt-ADS including the accelerator: 1.5 times of that of 3000 MWt-LWR.

The increment of electricity generation cost was calculated considering the difference of throughputs between in dedicated P-T and commercial fuel cycle. In partitioning process, heavy metal is 36 kg (FP, MA, 0.1% of U and Pu for 33 GWd/tHM) per 1 tonne of fresh fuel. In one ADS, MA inventory is 3 000 kg and this is the throughput of a dedicated ADS fuel cycle. It is one hundredth of the annually-discharged spent fuel from 12 LWRs. In the calculation, the cost breakdowns in Tables F.1 and F.2 were used for nuclear power generation and fuel cost in Japan.

The result of cost analysis is the following:

- capital cost increment: 5.4%;
- operation cost increment: 12.5%;
- fuel cost increment including partitioning: 7.7%.

This leads to 7.2% increase in electricity cost due to introduction of P-T. Selling the extra 230 MWe from ADS compensates the incremental cost and the net increment of electricity cost is 5.4%. When Actinide Burner Reactor is used instead of ADS, the cost increase is 3.8%. For this analysis, the same construction cost of ADS and ABR is assumed. The cost increase for ABR is smaller than ADS due to the fact that the construction of an accelerator and electricity for accelerator operation are not needed since ABR does not need an accelerator

Table F.1 **Cost breakdown of nuclear power generation in Japan** [6]

Item	Fraction
Capital	64%
Operation	23%
Fuel	13%
Total	100%

Construction cost of LWR: 340 000 yen/kWe

Table F.2 **Fuel cost breakdown** [205]

Item	Fraction
Mining and milling	10%
Conversion	2%
Enrichment	18%
Fabrication	24%
Spent fuel transportation	10%
Reprocessing	31%
Waste disposal	6%

Total	100%

4. Conclusion

As can be deduced from this short overview of cost assessment studies, most figures cited in this section are gross estimations which are not based on thorough technico-economical studies. The given cost data are merely indicative values extrapolated from present fuel cycle data for the MA and the FP partitioning and fuel refabrication operations. The development costs for dedicated transmutation or burner reactors are not included. The cost estimations for ADS based transmutations are still more speculative since no such facility at pilot scale exists at present.

References

[1] Lelièvre, D., *et al.*, *Perspectives and Cost of Partitioning and Transmutation of Long-Lived Nuclides,* EUR-17485-EN, pp. B72 (1997).

[2] Venneri, F., *et al.*, "Accelerator-Driven Transmutation of Nuclear Waste (ATW): Status, New Concepts, and Future Development", LANL ADTT-Project Office Presentation to DOE (1995).

[3] Krakowski, R.A., "Accelerator Transmutation of Waste Economics", *Nuclear Technology*, 110, (1994).

[4] Fernández, E., *et al.*, *A Preliminary Estimate of the Economic Impact of the Energy Amplifier,* CERN/LHC/96-01 (EET), (1996).

[5] Mukaiyama, T., *et al.*, "R&D Strategy for Partitioning and Transmutation under OMEGA Programme and Neutron Science Project of JAERI", *5th OECD/NEA Information Exchange Meeting on Partitioning and Transmutation of Actinide and Fission Product*, Mol (Belgium), (1998).

[6] Suzuki, T., "Cost Analysis of Various Electricity Sources in Japan", Report of Nuclear Energy Research Committee, pp. 2-52, Atomic Energy Society of Japan, 1996, (in Japanese).