*Annex 9*

# NUCLEAR FUEL CYCLE COSTS VERSUS BURN-UP

## 1. Introduction

Over the past decade the discharge irradiation level (burn-up) of PWR and BWR fuel has increased steadily. This development is mainly attributable to the increased economic benefit that is associated with higher fuel burn-up. This benefit comes from the reduced throughput of fuel that results from higher burn-up. This is particularly noticeable in the costs for fuel fabrication and back-end services where the price paid relates to a unit mass of fuel. As a result the adoption of higher burn-up has resulted in substantial savings in fuel cycle costs. The question of the economic potential of moving to even higher burn-ups beyond the present range is of great interest.

## 2. Base estimates and input data

The economic evaluation of increasing the burn-up of uranium fuel was addressed by an IAEA multinational study called *Water Reactor Extended Burn-up Study (WREBUS)*[11] which was performed in 1990-91. Eight countries (Belgium, France, Czechoslovakia, USSR, Germany, Korea, UK and US) provided contributions. In this study, a broad range of technical boundary conditions, i.e. reactor type (PWR, BWR), power output (440 MWe to 1 300 MWe) and cycle length (12 to 24 months cycles), was considered.

All the WREBUS fuel cycle cost calculations were carried out in 1991 money values and related to the unit cost of a reload once the equilibrium fuel cycle had been obtained. The fuel cycle was based on reprocessing as the spent fuel management option but credits for the recovered plutonium and uranium were not considered for reasons of simplicity.

The burn-up range of interest was from 40 MWd per kg U up to 60 MWd per kg U. This was considered to cover a set of values which should be technically attainable although no detailed technical cases were in existence to support the upper end of the range. Undoubtedly, research and development work would be needed and the costs of this would need to be taken into account in practice.

## 3. Comparative fuel costs

In this annex, the economic effect of increased burn-up has been evaluated by using the reference prices from this present study (see Table 9.1) and applying them to the technical spectrum of cases (with the exception of VVER reactors) that were used in the WREBUS study. This resulted in the range of fuel cycle costs which is shown in Figure 9.1. For comparison, the fuel cycle cost for the reprocessing reference case from the current study is shown within the range derived using the WREBUS technical data.

Table 9.1. **Economic input data (reference)**

| | |
|---|---|
| Uranium purchase | \$50/kg U (in 1990)<br>escalation 1.2% p.a. |
| Conversion | \$8/kg U |
| Enrichment | \$110/SWU |
| Fabrication | \$275/kg U |
| S.F. transport | ECU 50/kg U |
| Reprocessing | ECU 720/kg U |
| VHLW disposal | ECU 90/kg U |
| Discount rate | 5% p.a. |
| Tails assay | 0.25% |

Figure 9.1 shows that, for the whole spectrum of reactor types and operating conditions considered, no minimum fuel cycle cost was found within the burn-up range considered, i.e. within this burn-up range, it appears desirable to go to the highest technically possible burn-up.

## 4. Variation of economic input data

The results of the calculations are sensitive to the variation of the economic input data. The parameters having the greatest influence are the prices for back-end services and the discount rate, the former being the more important.

Increasing the burn-up of the fuel leads to a reduction in the quantity of fuel used for a given amount of electricity produced. Regardless of whether the reprocessing or direct disposal option is chosen, the effect on the unit fuel cost of any increase in the price for back-end services can be reduced by increasing the fuel burn-up. The effect may not be so great for the direct disposal option where storage, encapsulation and disposal prices will be geared to the overall fuel quantity to be managed. This is not the case with reprocessing where a competitive market exists and prices are quoted per unit mass of fuel to be reprocessed.

## 5. The economic effect of cycle length

Comparisons of the economics of different cycle lengths depend on a number of factors which are not specifically related to nuclear fuel cycle costs (less shut-down time, fewer refuelings, replacement power costs, etc.). Nevertheless, it can be deduced, from a rather complex comparison which was made for the WREBUS study, that longer cycles tend to shift the economic optimum to higher burn-up values.

## 6. MOX fuel

As discussed above, for uranium fuel, disposal costs related to the amount of heavy metal to be disposed can strongly influence fuel cycle costs as a function of the discharge burn-up. Therefore, the resulting reduction in the fuel cycle costs is more distinct with higher values of specific disposal costs.

In a similar way, fuel fabrication costs can influence fuel cycle costs. As a result, high specific fabrication costs, leading to fuel cycle costs with a high share of cost components which are strongly influenced by the energy worth of the fuel, as is the case with MOX fuel, cause significant decreases of fuel cycle costs when the burn-up is extended. This relationship is qualitatively shown in Figure 9.2 which compares uranium and MOX fuel cycle costs assuming constant fabrication costs for each type of fuel.

Taking into consideration the dependence of fuel fabrication costs on the fuel burn-up or the initial fuel enrichment (e.g. additional shielding required for MOX fuel fabrication), according to current information, the economic effects which are shown in Figure 9.2 would not significantly change.

## 7. Conclusions

Based on the above discussion, the following can be derived:

– Given the reference set of economic input data (as shown in Table 9.1) no minimum fuel cycle cost was found for burn-up values up to 60 MWd/kg U. It is to be noticed that even small improvements in fuel cycle costs can result in considerable yearly savings for nuclear power plants (for example, 0.1 mills/kWh equals to approximately 1 million dollars per year for a 1 300 MWe plant).

– The most important parameters contributing to fuel cycle cost benefits from burn-up extensions are the back-end costs and the discount rate, with back-end costs being much more important than the discount rate.

– The sensitivity of the results, and in particular the derivation of a minimum value of fuel cycle costs, is due to the interaction between back-end costs and the range of variation of the other economic input parameters which are primarily affecting fuel cycle costs. Thus, for example, the discount rate may have a significant effect on deriving the minimum value of the fuel cycle costs as a function of burn-up if back-end costs are related to the generated electricity rather than to the quantity of fuel.

– With regard to MOX fuel, an additional economic incentive for burn-up extensions results from the considerably higher share of fuel fabrication costs to the total fuel cycle costs. The quantitative impact of this economic effect on the total fuel cycle costs depends partially on the percentage of MOX fuel assemblies of the reload.

– In PWR plants, especially those operating at high coolant outlet temperatures and utilising zircaloy fuel cladding, water corrosion has been a limiting problem. Recent developments of new cladding materials (e.g. duplex cladding) enables a shifting of the cladding corrosion limit to substantially higher burn-ups in the future.

Figure 9.1 **Fuel cycle cost results for reference economic input data and a range of technical characteristics**
(WREBUS study)

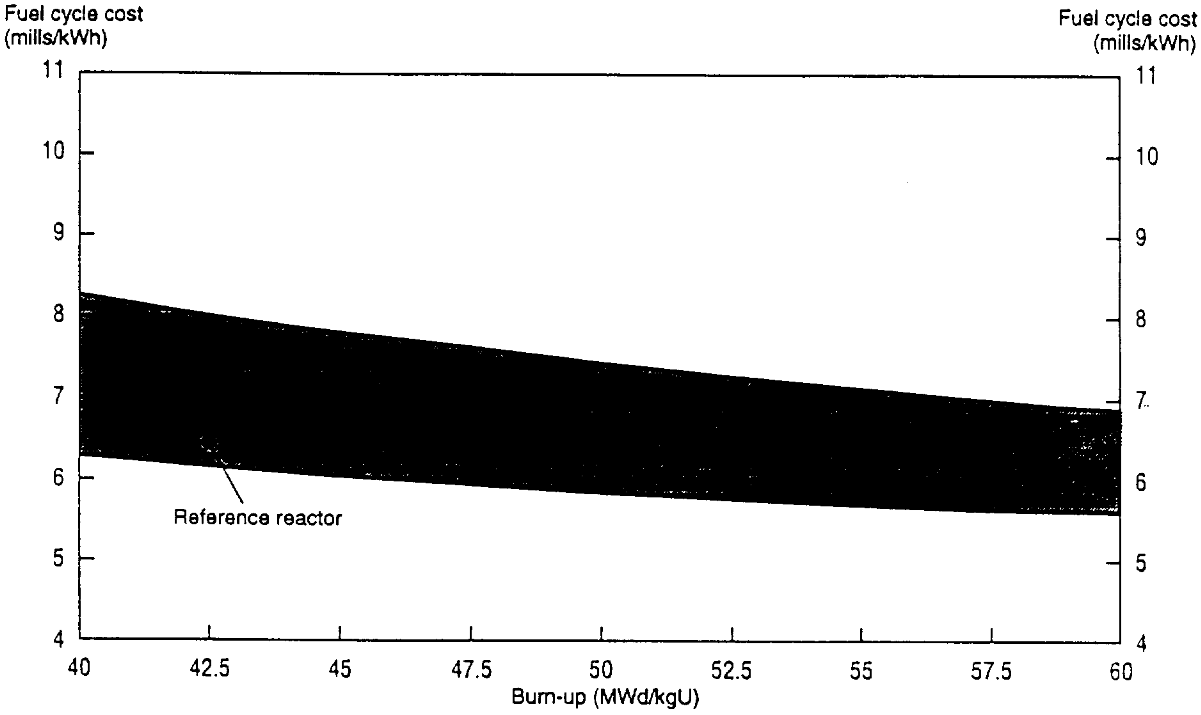
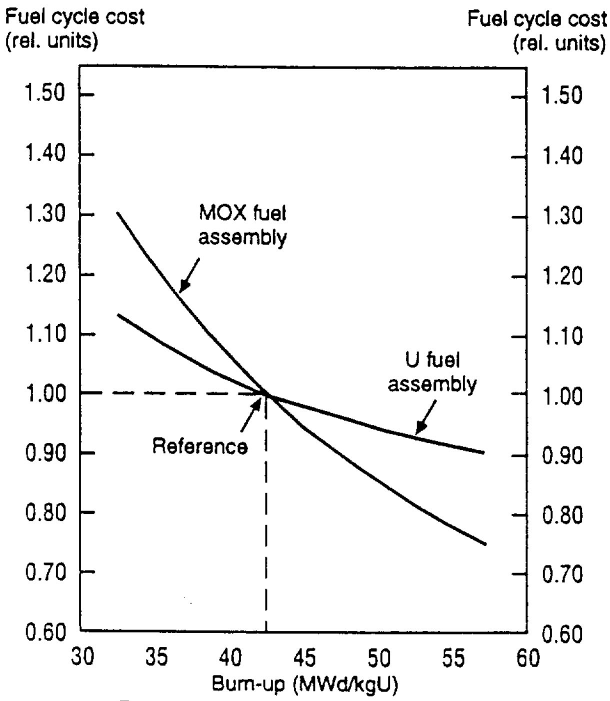
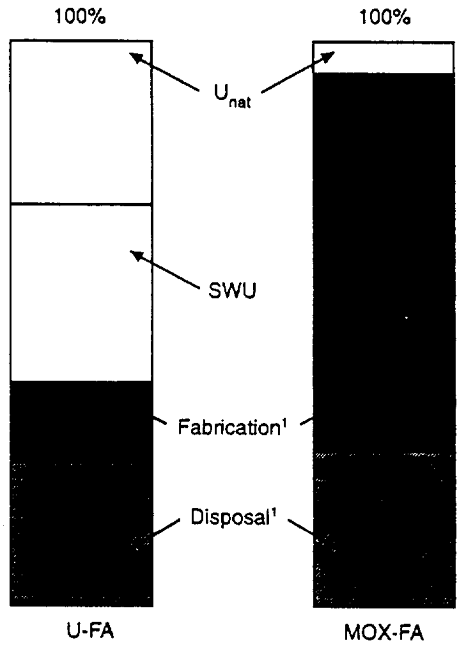



Figure 9.2 **Comparison of U and MOX fuel assemblies**




Fuel cycle costs as a function of burn-up




Structure of fuel cycle costs

1. Cost components strongly influenced by energy production.