Nuclear Development

Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles

A Comparative Study

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

neutrons out of the core. The second is the potential to increase inadvertently the strength or the effectiveness of the source neutrons in a way that increases power density. Penetration of containment is a third issue and will be discussed later in Section 5.4.

5.3.4.1 Beam tube flooding

Should the beam tube wall or window loose integrity, then in the cases of Na or Pb-Bi cooling, the coolant would immediately flood the evacuated beam tube to a level at least the height of the coolant free surface. Although the spallation source would move to the upper regions of the flooded column and its neutronic coupling to the transmuter core (i.e. its effectiveness) would drop to nearly zero, an increase in reactivity would result from extra neutron reflection due to filling the tube with coolant which acts as a reflector more than an absorber. It will be essential to design the ADS so that this event would not take the core into prompt criticality. Scoping calculations for a 840 MWth Pb-Bi cooled system with a 40-cm diameter beam tube indicate that reactivity additions in the range of 0.5% $\Delta k/k$ (i.e. several dollars) are possible.

The beam tube flooding scenario will be one among many of the considerations for setting the sub-criticality level on the transmuter fissile loading.

5.3.4.2 Source importance changes; buffer voiding event

The "effectiveness" of the neutrons which are injected into the sub-critical transmuter lattice depends not only on properties of the transmuter lattice core itself but also on the spatial position and the energy spectrum of the source neutrons. Current ADS design concepts place the spallation target near the centre (axially and radially) of the transmuter lattice where its is most effective. When central placement of the target is the design approach, abnormal events which move the source location off centre (e.g. the beam tube flooding event described above) will reduce the effectiveness of source neutrons, and without changes in reactivity the neutron population and associated ADS power level will tend to decrease.

In addressing the energy dependence of S*(R,E) for source neutrons, it is noted that after the first flight leading to a fission event, multiplication in the subsequent prompt fission chain will be determined by the familiar formula for sub-critical source multiplication shown in Eq. (3), which depends on the properties of the transmuter core geometry and composition ß and particularly on the η value of the transuranic fuel averaged over the fission neutron emission energy spectrum as slowed down by the lattice materials. This fission-multiplied neutron energy spectrum never exceeds the top end of the fission emission spectrum at a few MeV. The fission power is directly proportional to this fission-multiplied neutron source strength as shown in Eq. (4).

However, the spectrum of spallation neutrons has a tail in its distribution which goes well beyond 6 MeV as shown in Figure 5.2. Therefore, spallation target designs incorporate a row of "buffer" assemblies around the target, filled with coolant and other scattering materials to moderate the energy distribution of the neutrons down to the MeV range and to spread their directions of emission so as to produce a more nearly isotropic source. Should this moderator material be somehow removed, the most energetic spallation neutrons would pass through the buffer on their first flight with little or no scattering moderation and undergo their first fission interaction at high neutron energy (e.g. > 6 MeV), with a higher value of η than intended and releasing substantially more fission neutrons. All subsequent events in the fission chain would continue as before. Thus a vulnerability exists in that an abnormal loss of moderation in the buffer would significantly raise the power to flow ratio at a fixed value of sub-criticality.

Since an abnormal buffer voiding event will constitute a vulnerability in any case, this mechanism can perhaps be put to good use and included among the options considered in Section 6.3.1.2 for deliberate control of the transmuter power level in the face of declining reactivity with burn-up.

5.4 Containment, shielding, and decay heat removal

The traditional FR design approach for assuring the containment of radioactivity is based on defence in depth with three containment boundaries: the fuel cladding, the primary coolant system boundary, and the containment structure. Each barrier has provisions for cooling so as to maintain its integrity in both normal and abnormal conditions. The outermost barrier, the containment structure itself, must be designed to ensure containment when the middle barrier is vulnerable during refuelling operations, and it must provide a highly reliable channel for transmitting decay heat to an exterior ultimate heat sink without loss of containment even under severe accident conditions. The strength requirements of the containment derive from considering hypothetical core disruption events and the amount of internal heat, pressure, and missiles that they could conceivably generate. While many containment issues are similar for FR and ADS, several are peculiar to features of the ADS.

5.4.1 Proton beam tube penetration of containment barriers

The presence of a spallation target at the centre of the transmuter core and the arrangements made to direct a high energy proton beam on to it are features totally absent from a fast reactor. Several safety issues related to the containment function, but also pertaining to refuelling, shielding and coolability, are discussed here.

An obvious issue raised by the beam tube of an ADS is that of maintaining multiple containment barriers. For linac-driven ADS, the proton beam tube penetrates the containment-building barrier. (Cyclotron-driven ADS could conceivably place the cyclotron inside the containment structure and avoid penetrating the outermost of the three containment barriers). In both cases, the proton beam tube itself (and the proton window if one is employed) comprise a re-entrant segment of the primary coolant boundary barrier.

The beam tube penetration of the containment boundary is similar in character to the secondary coolant loop penetration of a standard sodium cooled fast reactor or the steam line penetration of a thermal reactor, where safety-grade closure valves can be provided. The multi-megawatt proton beam itself, however, comprises an ADS-specific hazard to the integrity of the tube and the fast acting valve alike, because beam misalignment would promptly melt through the tube wall and if not immediately tripped the beam would melt the fast acting valve.[50]

The beam tube as a re-entrant segment of the primary coolant boundary is topologically similar to an intermediate heat exchanger tube in a FR. In the latter case, the tube contains secondary coolant at ambient pressure whereas in the former it is under vacuum.[51] Again the beam misalignment hazard to proton beam tube integrity and the particularly hostile environment experienced by the beam window are unique to ADS design. Ruptures of either window or tube wall will open up a connection into vacuum so that flows of atmosphere will initially be inward into the accelerator cavities; moreover, loss of vacuum will itself trip the beam as a response to sparking in the HV accelerator cavity. Longer-term containment must be addressed.

50. Upon loss of vacuum, sparking in the acceleration cavity would normally lead to accelerator trip.
51. In the BREST reactor concept an integral steam generator replaces the intermediate heat exchanger, and the tube walls separate high-pressure steam from ambient pressure coolant.

For pressurised gas-cooled ADS, loss of integrity in the beam tube or window represents one of the ubiquitous potential pathways to loss of coolant.

An ADS-specific challenge to the primary coolant boundary barrier may derive from the position of the bending magnet. If, on the one hand, a top-entry beam tube is employed, then the multi-ton bending magnet is placed directly above the transmuter vessel, where it represents a falling hazard in the event of structural flaws or damaging seismic accelerations. If, on the other hand, the beam penetrates the transmuter vessel from the side so as to eliminate this hazard, and penetrates at an elevation below the surface of the liquid metal coolant, then the beam tube provides a vulnerability for coolant draining on failure of nozzle weld or window. With gas cooling, vulnerability to loss of coolant is independent of entry arrangement.

5.4.2 Refuelling and shielding

For the most part, the maintenance of sub-criticality, of containment, and of decay heat removal during refuelling operations present issues common to ADS and FR. The presence of the proton beam tube, however, presents several challenges which are unique to the ADS.

The most obvious is the issue of shielding. Because an unobstructed flight path is essential to deliver the proton beam on target, the opportunity for shielding inside the beam tube is foreclosed. The beam tube comprises a radiation streaming path of significant cross sectional area for gammas and neutrons from the centre of the transmuter core to the exterior of the primary coolant vessel, or even beyond the containment building and into the proton acceleration structures. If the beam enters from the top, the beam tube gives rise also to a straight neutron streaming path from the core centre to the region of the bending magnets, causing their activation by neutron bombardment. If the beam enters from the side, the streaming path extends further into the accelerator segments themselves with the potential for activating them. Bending magnets could provide a labyrinth path, but would be subject to activation of the magnet itself so that shielding and appropriate maintenance procedures become necessary. Both activation of structures outside the vessel and direct radiation streaming present challenges to keep worker dose exposures low during operations and maintenance.

If the beam enters from the top, then bending magnets and their shielding are located directly above the core, and difficulties of access may arise in refuelling, notably through interference with the polar crane and constraints on height. Nonetheless, if top entry beam geometry could accommodate refuelling, it would be beneficial in that the fuel-loading pattern would be azimuthally symmetric, as is not possible with other beam entry orientations.

If the beam enters from the side, interference with refuelling will be avoided, but the fuel-loading pattern will necessarily be azimuthally asymmetrical to accommodate the beam tube. “Teapot” configurations have been considered for conceptual ADS layouts; the beam enters the transmuter vessel at an angle from above, down the spout, and thereby avoids the loss-of-coolant vulnerability, interference with refuelling, and the vulnerability to impact on the magnet. Like the side entry configuration, the teapot approach introduces an asymmetry in core layout and refuelling, giving rise to radial and azimuthal distortions of power density.

The safety relevance of distortions to power density arising from the side and the teapot beam entry configurations is not known without analysis, but will pertain to ensuring cooling, and to accuracy in predicting fissile burn-up. These could affect certain approaches to guaranteeing the specified degree of sub-criticality and in any case will increase uncertainties in the margins from criticality in recycling facilities assumed in sizing process equipment and to control recycle operations.

5.4.3 Decay heat removal

A heat transport pathway sized at 0.1 to 1.0% of rated power must be maintained to the ultimate ambient heat sink from the fuel pins, and must be guaranteed to function under conditions following a severe accident. Enough thermal storage capacity must be provided to absorb the temporary initial excess of decay heat over the capacity of the heat removal channel.

Traditionally in FR plants, the heat transport path to the balance of plant (BOP) heat engine equipment carries a requirement for safety-grade removal of decay heat. Recent fast reactor designs have relied instead on dedicated redundant heat transport circuits from the reactor vessel pool to the air outside the containment structure and often configure them to operate continuously and "passively" on the basis of buoyancy-driven flows. The "pool" category of liquid metal cooled FRs utilises double walled vessels to assure that primary coolant is confined to the pool even if the primary vessel leaks, and the coolant inventory is maintained by this second "guard vessel" to cover the core and the heat exchange surfaces dedicated to removing decay heat (DRACS). With thermal ratings of 1 500 MWth the outer of the two vessels (the guard vessel) is sometimes declared the (close-coupled) containment structure and its outer surface is itself cooled by a natural draught of ambient air (RVACS) as the final link in the decay heat removal channel; (some licensing authority regulations do not accept this close coupled containment).

For liquid metal cooled ADS with top or teapot entry beam tube, a similar approach should apply with no additional issues. For gas cooled ADS or liquid-cooled ADS with a side entry beam tube, the issue of loss-of-coolant accidents would have to be addressed as for LWRs and HTGRs.

Whatever the design for decay heat removal (RVACS, DRACS, or BOP), safety-related testability will be required for ADS as for FR.

5.4.4 Containment loading criteria; HCDA termination

The size (internal volume) and design pressure rating of containment structures for LWRs and FRs have historically been determined by the loadings they must sustain in their role as the final barrier to reactivity release, even in the event of a severe accident which leaves the fuel cladding and primary coolant boundary in tatters. For water-cooled thermal reactors, the determining event is the loss of coolant accident and large hydrogen deflagration (from Zircaloy-water reaction at high temperature); for fast reactors it is the Hypothetical Core Disruptive Accident (HCDA).

Fast neutron lattices of all kinds are not in their most reactive configurations; changes which decrease surface to volume ratio will reduce neutron leakage and increase reactivity, conceivably to reach super-prompt criticality. This unavoidable vulnerability has led to decades of work on severe accident evaluations to determine bounds on energy release resulting from hypothetical core disruption, so as to provide the information for sizing and design of the containment building to contain that release and release rate. Early small prototype sized metal fuelled FRs relied on fuel dispersal to quench the postulated prompt critical burst while later, the larger commercial-sized oxide fuelled FR relied on prompt-acting negative feedback from Doppler absorption in fertile material contained in the fuel to reduce energy release from the burst. The recent modular-sized ALMR relied on melting of the metal fuel and its immediate dispersal by fission gases to preclude a prompt critical burst. In all cases the goal was to quench the chain reaction quickly and thereby limit the energy released, to put lesser demands on the containment structure.

The absence of a fertile Doppler feedback combined with potentially low neutron leakage in an ADS core built of a tough fuel capable of high energy storage will quite obviously necessitate a

changed strategy for terminating a severe accident. If, in response to an abnormal initiator, a large ADS composed of fertile-free fuel were to reach prompt criticality, it would then present an exceptionally severe challenge to containment because it lacks both of the historically employed mechanisms to quench a prompt burst in a fast reactor, i.e. it has neither the Doppler feedback in large cores of robust oxide fuel nor the prompt dispersal achievable in small cores of low-melting fuels [150,151].

Both the lead-cooled and gas-cooled versions of FR and ADS have high volume fractions of coolant in the array with greater vulnerabilities than in sodium-cooled FRs. With the geometry for gas cooling, the disrupted fuel pins would block the neutron streaming paths provided by the coolant channels, and thereby add reactivity.[52] With lead cooling, the high density of the coolant itself would offer inertial resistance to spatial disassembly of the lattice thereby requiring a larger deposition of energy for ultimate disassembly and quenching.

It will be important for the ADS safety strategy to devise means of precluding prompt bursts in HCDA using intrinsic properties of the lattice, as was possible for the modular ALMR. An extra degree of freedom is available in the ADS design to cope with HCDA initiators; it is the initial degree of sub-criticality. If it can be made large enough to overcome the reactivity addition of any plausible compaction or coolant voiding, then the potential for super-prompt criticality can perhaps be foreclosed by design. The need to do so provides one of the strongest incentives for designs which consume the excess neutrons generated in a pure transuranic fuel by using internal neutron absorbers integral with the fissile within the fuel pin, rather than by relying on neutron leakage.

Upon fuel pin disruption – even in the absence of prompt bursts – the issue of re-criticality in the fuel debris must be addressed. The situation might turn out to favour the lead-cooled option where the fuel would float and possibly disperse radially as dross on the lead surface. For the gas and sodium option, the traditional FR re-criticality issues will apply.

5.4.5 ATWS initiators; passive versus engineered safety approach

In design and safety considerations for a FR, transients with scram constitute part of the design basis while Anticipated Transients Without Scram (ATWS) are often considered as Beyond Design Basis and used for sizing the containment structure and its pressure rating. Rod run-out (transient over-power) without scram (TOPWS), loss of heat sink without scram (LOHSWS), and loss of pumping action (flow) without scram (LOFWS) are considered whereas loss of coolant is not considered credible for double-vessel pool designs with liquid metal cooling.[53]

For FRs, the term “scram” refers to inserting the bank of safety rods, always with a single rod assumed to be stuck. Depending on specific licensing requirements, simultaneous tripping of primary and secondary pumps may also be assumed. For ADS the term “scram” has not yet been defined, but must certainly mean that at least the proton beam is turned off.

In some FR designs, completely passive accommodation without damage of LOFWS and LOHSWS events has been designed in and even demonstrated in pilot-scale plants such as RAPSODIE and EBR-II [138]. This FR passive safety approach has relied on thermo-structural

52. Particle-fuel gas-cooled fast reactors require careful scrutiny to identify their potential strengths and vulnerability.
53. The leakage through the double vessel has been considered for Superphenix to represent the “Ultimate (BDB) for which public evacuation procedures must be defined. US licensing procedures for CRBR used the HCDA resulting from a transient over-power driven by loss of flow (positive sodium void worth) as the basis for public evacuation procedures.

reactivity feedback to self-regulate heat production to match the available heat removal rate [150,151]. And in the case of TOPWS, a favourable passive safety response can be demonstrated for FRs designed to have near-zero reactivity loss upon burn-up, so that very little excess reactivity is vested in the control rods.

The favourable performance of ADS in reactivity insertion (TOPWS) events has been well documented for reactivity additions which do not take the system super prompt critical and where a beam trip occurs in time to avoid fuel damage [145,146]. Loss-of-heat-removal events in an ADS lead quickly to overheating if the beam remains on as has also been well documented [145,146]. Even with the beam off, it is useful to suppress multiplication of delayed fission neutrons by reducing reactivity when heat removal has failed.

In keeping with the trend in FRs to place increased emphasis on passive means to reinforce active engineered safety systems, several passive safety features affecting cooling rates and source strength are currently being considered for ADS:

- Natural convection at full or significant power levels (to accommodate LOFWS) [146].
- Passive beam interrupts or relocation to a position of lower effectiveness upon overheating of coolant (to accommodate LOHSWS) [146].
- Electricity to drive the accelerator derived not from the grid, but instead fed back from the ADS itself (to accommodate LOHSWS, LOFWS) [151].

Passive power self-regulation based on thermo-structural reactivity feedback, as has been exploited for fast reactors, is precluded by the fundamental characteristic of sub-critical source-driven systems. For an ADS, the operating point is offset from prompt criticality by $(\beta - \rho_o)$ where $-\rho_o$ is the sub-critical operating point. The offset is only β for a critical reactor. As is evident from the denominator in Eq. (6), the effect is that the power level in an ADS is less sensitive than in a reactor to reactivity feedback. Moreover, as is also evident from the inhomogeneous source term in Eqs. (6) and (7), the power can never be driven to zero by reactivity changes as long as the spallation source is non-zero. The ADS must therefore adopt different strategies for employing passive concepts to keep heat production and removal in balance. Specifically, it needs some means for passively adjusting the strength or effectiveness of the source in response to power changes. Options include powering the accelerator with ADS-generated electricity[54] [152], or source-transmuter coupling dependent on coolant temperature or density. Absorber or moderator curtains in the buffer surrounding the source, or spatial relocation of the target (all activated by temperature or density changes in the coolant) affect coupling and might offer opportunities to apply passive source feedback analogous to the passive reactivity feedback successfully exploited and demonstrated in fast reactors as the passive means to self-regulate the rate of heat production to match removal.

Among research efforts on safety in ADS, applications of passive safety approaches to accommodating ATWS should be stressed, because the efforts for the past decade on FRs have shown significant potential for benefits.

5.4.6 Activation products

In both FRs and ADSs, the activation of materials of construction affects safety, both by exposure to workers during operations, maintenance and decommissioning, and later as a long-term toxicity hazard attendant on waste disposition from the decommissioned plant. Since the function of the class

54. The exceedingly long time constant for feedback presents a major challenge with this option.

of ADS discussed here is to reduce the long-term radiotoxic legacy of nuclear energy, it is especially important that they should not add to it.

The issues of coolant activation and its effect on operational safety issues are similar for ADS and FR and were discussed in Section 5.3.2.2. Activation effects on long term waste management were studied by Oussanov *et al*. [153], who found considerable differences in the character of long-term residual activity arising from sodium, lead, and lead-bismuth coolants. For Na, 50 to 80 years of storage should be sufficient to allow unrestricted further use, for lead perhaps 1 000 years, and re-use is not feasible for Pb-Bi.

Spallation products and activated proton accelerator structures and beam tubes in an ADS are features not shared by a FR. The production rate of radiotoxic species depends directly of course on source strength, providing an incentive for small levels of sub-criticality. The study of long-lived toxicity generated in spallation reactions is at an early stage [154,155]. The mass spectrum of spallation products spans the range from tritium up to the mass number of the target material, and the relative yields depend on the energy of the incident proton beam. Notably, long-lived alpha-emitting rare earth spallation products (e.g. Gd, Sm, and Dy isotopes) could be avoided through use of a target of mass number less than 145 amu – e.g. tin. Preliminary model studies on yields of alpha-emitting rare earths in heavier targets suggest [156] their significance relative to polonium (in Pb-Bi targets) and generally vis-à-vis toxicity reductions obtained by transmuting technetium and iodine.

Beam loss is one of the crucial design factors in the high-current accelerators required for ADS; it also activates accelerator structures, affecting both operations and ultimate disposition of equipment. Detailed calculations were made [157] for the 100 MeV to 1 GeV section of a normal-conducting linac assuming a loss of 0.48 nano A/m (i.e. 1.2×10^{-8} proton/meter) in a 40 mA machine based on the TRISPAL design. Ordinary concrete shielding of between 1 to 4 metres would be required to limit surface dose rate to 1 mrem/h. Misalignment of the beam (40 mA) into the structures for 50 μ s. was also studied and found to produce activation which has largely decayed away after about 15 min. Like the spallation product issue, structural activation in high-current proton beams is at an early stage of investigation.

5.4.7 Propagation of local faults

Issues of local faults (such as breached fuel clad or plugging of coolant channels) which could be propagated and exacerbated into full core events are common to FR and ADS. They have been extensively studied for sodium cooling with oxide and metal alloy fuels where it is shown that chemical interactions between coolant and fuel should preferably avoid forming low-density products. Also, chemistry control of Pb-Bi alloy coolant to avoid both cladding attack and sludge formation has been thoroughly studied in Russian military experience, but scant experience exists outside Russia. It is clear that extensive, multi-year in-pile irradiation testing campaigns will be required for any new combination of fuel, cladding and coolant, as in every one of the inert matrix (non-fertile) fuels considered for TRU/MA ADS burners.

5.5 Safety in fuel cycle facilities

Complete consumption of the transuranic feedstock requires multiple recycling because the neutron fluence required to fission all the transuranic atoms exceeds the neutron damage endurance of the cladding material. Three of the five cardinal safety functions (containment, shielding, and removing decay heat) are identical whether the fuel is in core, out of core in transfer casks, or out of core in a recycle facility; thus the discussions of such issues already given for the transmuter core carry over to the fuel cycle facility as well. However, in the recycling facilities the cladding is

purposely removed. Instead of matching heat production and removal, the cardinal safety requirement out of the core becomes simply “avoid criticality”.

The safety issues related to containment, shielding, and decay heat removal during fuel transfer and recycle operations are essentially identical for the ADS and FR fuel cycles, but the use of fertile-free fuel in the ADS or FR cycle will affect the functional requirement for avoiding criticality because the fast-spectrum critical mass of pure TRU is small. Pure transuranic fuel, with an η of ~1.8 and a fast-spectrum critical mass of 5 to 15 kg, will have to be handled in small batches. Particular care will have to be taken in accounting for effects of reflection and inventory coupling when designing process equipment and deciding on layout. Similarly, moderating materials will have to be excluded or carefully controlled within the casks and the recycle facility.

Criticality constraints within recycle facilities add still further weight to the preference for use of parasitic absorber material, intimately blended with the fertile-free transuranic fuel itself and chemically similar to a rare earth or actinide so as to follow the transuranics through every stage of recycling and refabrication.

Whether in ADS or FR designed for incineration, shielded remote operations are required because the transuranic elements include strong neutron emitters (e.g. ^{244}Cm), spontaneous fissioning isotopes (e.g. ^{240}Pu), pyrophoric chemical characteristics, and low-temperature volatility (e.g. ^{241}Am). These materials must be handled in remotely operated and remotely maintained shielded facilities under inert atmospheres. Their small critical mass demands that process control and material inventory tracking meet high standards of accuracy and that operations be conducted under strict discipline. Atmosphere control of the hot cells (maintaining inert atmospheres to address pyrophoricity) and discharging aerial effluent only through filtered channels places special requirements on seismic design of structures and equipment. It also makes conflicting demands to maintain effluent filtering during abnormal events (such as a breach of cell containment) while stopping flows in order to smother fires following the access of air to pyrophoric materials. Such issues are peculiar to the presence of TRU or MA fuel types and are common to fuel cycle facilities for FR and ADS alike.

5.6 Conclusions

This chapter analysed the safety-related challenges of a specific class of ADSs employing a fast neutron spectrum and solid, fertile-free fuel with the primary mission of transmuting transuranics or minor actinides.[55] Multiple options for addressing nearly all relevant issues have been developed in the framework of an impact matrix of safety functions required for each distinctive design feature of an ADS, and each distinctive design feature has been tracked back to a specified mission element.

From this analysis, the following conclusions can be drawn:

- The ADS’s dynamic response to changes in reactivity or neutron source strength is the area of greatest difference in safety characteristics between fast reactors and ADSs and an area where no precedents exist in the fast reactor experience base.

- The primary cause for this is (a) the external neutron source which can provoke rapid and, depending on the sub-criticality level, large neutron-kinetic responses, unmitigated by the delayed neutrons, and (b) the fertile-free fuel which features very weak reactivity feedbacks, especially from the Doppler effect.

55. A summary of this chapter has been reported in [158].

- This puts high demands on the control actuators, the fuel behaviour, and the heat removal processes. In particular, the strong dissimilarity of the neutron-kinetic and thermo-structural time constants requires the fuel to be capable of sufficient adiabatic heat storage.
- The weak Doppler effect exhibited by fertile-free fuel affects the energetics of hypothetical core disruptive accidents. If such accidents have to be taken into account in the safety analysis of an ADS, a prompt quenching mechanism relying on a phenomenology other than the traditional Doppler effect will have to be developed.
- The management of the surplus neutrons in sub-critical cores with fertile-free fuel by means of neutron leakage and/or absorption involves delicate trade-offs which affect core design. This applies particularly to TRU burners which feature a high burn-up reactivity loss.
- Regarding passive safety principles, it appears that means for passive decay heat removal are already available, but innovation is needed to achieve passive self-regulation of power.

6. COST ANALYSIS OF P&T

6.1 Introduction

Economics represents an important pillar of sustainable energy development, as was mentioned in Chapter 1. This chapter, therefore, aims at addressing the economics of the range of P&T options examined in this study. This economic assessment is presented only in terms of "top-level" cost trends, and is not supported by the kinds of detail required of a rigorous market survey. These limitations result from the large uncertainties in the technologies to be deployed and the associated cost uncertainties.

As suggested above, the cost analysis of advanced nuclear systems and fuel cycles calls for prudence, since the cost assessment for many elements (e.g. TRU/MA-fuel fabrication and reprocessing) must be based on preliminary conceptual studies where little or no (pre-)industrial experience is yet available. The present study addresses the cost analysis by first defining and evaluating unit costs (e.g. $/kg, $/We, $/kg.y, etc.) for the different interconnected fuel cycle steps (see Section 6.2.2). These costs are then aggregated according a standard levelised costing methodology for the nuclear fuel cycle (NFC) (see Section 6.2.1 and [159,160]) and finally expressed as cost of energy, COE (mill/kWh), for each fuel cycle scheme. Because of the above-noted uncertainties, only energy costs relative to the reference LWR once-through fuel cycle (fuel cycle scheme 1) are presented. The intention of presenting relative energy cost is to emphasise relative differences between the various P&T approaches examined, rather than to present or attempt to make actual "market comparisons and assessments" in the form of absolute costs of energy.

The overarching goal of this cost study, i.e. to identify ways in which specific P&T approaches might be improved to become economically competitive under sustainable conditions, points to a "top-level" (highly aggregated) analysis using a range of unit costs (e.g. low, nominal, high) for the advanced fuel cycle options and operational-performance assumptions. While this methodology has known limitations [160-162], the Expert Group determined that it is the most appropriate for this generic cost analysis. However, it is clear that a definite priority or choice ranking of the schemes cannot be a principal goal of this kind (level) of cost analysis.

A "top-level" mass/energy-balance model[56] for the nuclear fuel cycle schemes is used to generate the material flows and inventories required to estimate annual charges for the cost-of-electricity (COE) evaluation. This model is also "top-level" in that, as in the neutronic analyses of the fuel-cycle schemes described in Chapter 3, an equilibrium steady-state is assumed as a simplifying assumption wherein steady-state mass flows and costs are expressed on a per-TWhe basis. The cost-base systems model performed an independent mass and energy balance and was adjusted to produce mass flows in rough agreement with the detailed neutronic analyses reported in Chapter 3. These mass flows (and inventories) and energy balances were then used in estimating annual charges, AC(M$/y), which were then expressed in COE(mill/kWh) units before final normalisation to the COE estimated for the once-

56. The reader is referred to references [163-166] for more details on the calculational methodology.

through LWR scenario (fuel cycle scheme 1). Specific input items for these calculations are, in addition to the input and discharged fuel compositions as evaluated in the neutronic analyses, the unit-cost database that was developed and reviewed by the Expert Group. While such a combined economics and mass/energy balance model is suited to evaluate the connectivity between economics and most other elements of sustainable nuclear energy, the focus in this study is primarily on COE-versus-environment trade-offs as driven by the combinations of technologies used to define the six principal fuel cycle schemes elaborated in Chapter 3. For the purpose of this combined analysis, the "environmental friendliness" is measured in terms of the TRU losses to the repository, to be denoted "LOSS parameter", which for TRU or its plutonium and MA components assumes the unit of kgTRU/TWhe. Other mass flows, for example the use of natural uranium and fuel fabrication requirements, were also calculated to derive the fuel cycle costs but are not reported in this chapter and are referred to in Chapter 3. Extension of this cost-base systems model has been foreseen to include additional metrics to evaluate nuclear energy systems.[57]

The present chapter first describes briefly the NFC systems model, and then elaborates and justifies the associated unit cost estimating relationships (CERs), that are based on a literature survey and iterative judgement by the Expert Group. The second part of the chapter will discuss the results of the levelised NFC costing model, with the presentation of key indicative cost trends and trade-offs concluding this part of the study. Although many of the choices for unit costs and related financial parameters are subject to uncertainty and compromise, an important goal of this chapter is to lay out in as much detail and clarity as is possible the basis for the unit-cost or CER choices made, to the extent needed to support recommendations for ways in which a given fuel cycle scheme may be developed along desirable economic lines, as well as for setting the course of respective future R&D for all of the P&T schemes that form the study agenda.

6.2 Nuclear fuel cycle model

The systems approach, methodology, and unit-cost database (CDB) leading to the costing results reported herein are described in this section. The basis and level of the NFC costing analysis is shown in Figures 6.1 and 6.2. The six principal fuel cycle schemes,[58] as introduced in Chapter 3, are represented in Figure 6.1, illustrating the essential elements of a generic fuel cycle as considered in this study. Figure 6.2 gives a breakdown and definition of key fuel cycle steps or "centres" where material flows and inventories have been tracked; each of the fuel cycle steps depicted in Figure 6.2 also served as a cost centre for conducting the respective economic assessment. Each of the twelve fuel cycle steps of the NFC described graphically in Figure 6.2 represents the finest resolution of the costing and TRU waste-disposal assessments that lead to the respective sustainability parameters. As mentioned before, these fuel-cycle schemes and, therefore, fuel cycle steps, are considered to be in steady-state conditions.

The next Section 6.2.1 focuses on the methods by which the equilibrium (steady-state) NFCs mass flows are estimated, as well as the procedure used to evaluate the COE (mill/kWh) and the LOSS (kgTRU/TWhe) parameters. Subsequently, Section 6.2.2 will describe the unit cost database.

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57. In a separate, independent study [167] based on this cost-base systems model and using the NEA cost base, a third metric intended to give a measure of proliferation propensity for a given NFC is also included. An approximate Multi-Criteria Analysis (MCA) is performed across all scenarios base on this quartet (cost, loss, resource, and proliferation) of metrics. Such an analyses, however, was not either within the charter or resources of the present study or Expert Group.

58. This generic fuel-cycle model also enabled the fuel-cycle scheme 3c to be modelled as a variant of the 3b scheme.

Figure 6.1. **Generic nuclear fuel cycle model showing the essential elements and options for a nuclear fuel cycle**

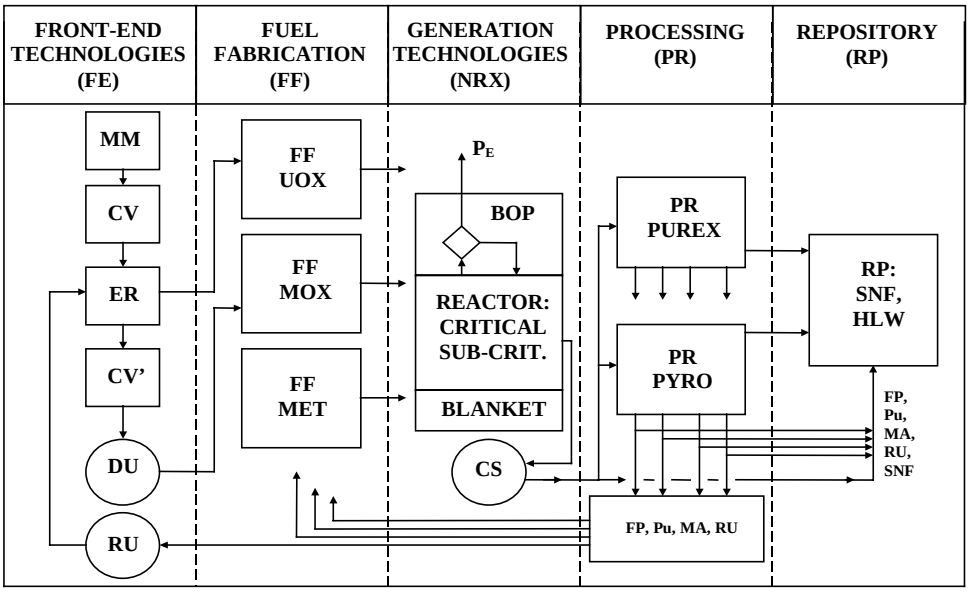
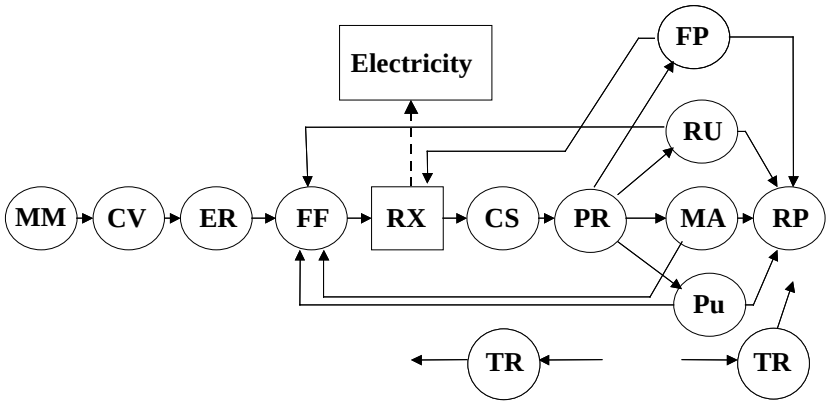


Figure 6.2. **Essential elements of the nuclear fuel cycle (NFC) being considered in evaluating key sustainability metrics for nuclear energy**



MM	**= Minig and Milling**	**RU**	**= Irradiated Uranium**
ER	**= Uranium Enrichment**	**MA**	**= Minor Actinide**
CV	**= Uranium Conversion**	**Pu**	**= Plutonium**
FF	**= Fuel Fabrication**	**TR**	**= Transport**
RX	**= Reactor**	**RP**	**= Repository**
CS	**= Cooling**	**FP**	**= Fission Products**
PR	**= Processing**		

6.2.1 Equilibrium NFC analysis

The simplified, steady-state material-energy balances in the "top-level" model are defined by the assumption of a standard net-electric grid capacity (P_E = 1 000 MWe) for each once-through LWR technology that, with the exception of fuel cycle scheme 5, drives the subsequent technologies in that

fuel cycle scheme. The subsequent technologies that operate in equilibrium with the LWR driver technology are sized to consume the plutonium or TRU generated therefrom. The energy generated by these subsequent reactor technologies in the fuel cycle schemes is then determined by the respective steady-state mass flows from the previous technology in the sequence and added to the total TWhe produced in the overall fuel cycle scheme. Table 6.1 lists the key technology parameters used to make this equilibrium material-energy balance. The parameters are carried over or derived from the neutronic analyses described in Chapter 3, although to maintain parametric independence, a separate material balance was computed instead of taking directly the per-TWhe mass flows from Chapter 3.

The reactor-dependent burn-up parameter BU (MWd_{th}/kg_{HMI}), the per-pass burn-up fraction BU_f, and the LWR "feed rate" are the main determinants of mass flows down-stream from the driving LWR technology. The input and output HM (heavy metal; U, Pu, MA) compositions, y_{HMi}, and y_{HMf} for each reactor type, along with the respective loss (to repository) fractions associated with the processing step that is a part of the particular technology, also drive these equilibrium mass balances.

Once the equilibrium mass flows to and from each of the NFC steps depicted in Figure 6.2 are determined for a given scenario or scheme, along with associated inventories based on assumed hold-up times for each step in the NFC (see Figure 6.1), unit costs, UC_{xx} ($/kg, $/We, or $/kg·y) are used to estimate the annual charges associated with each step xx of the NFC (e.g. $AC_{xx}(\$/y) = UC_{xx} \times MR_{xx}(kg/y)$, were MR_{xx} is the mass flow rate) with these annual charges being summed over the xx fuel cycle steps. The resulting total annual charge, $AC(\$/y) = \sum_{xx} AC_{xx}(\$/y)$, is summed over each of the reactor technologies (nrx) comprising a given scenario, and this total annual charge is divided by the total net annual electricity generation to give the cost of electricity, COE (mill/kWh), as follows:

$$COE(mill/kWhe) = \frac{AC(\$/y)}{8\,760 \sum_{nrx} P_E(nrx) p_f(nrx)} \quad (1)$$

where $P_E(nrx)$ and $p_f(nrx)$ are the net electric power and the plant availability, respectively, of reactor technology nrx (LWR, FR, ADS).

The TRU-loss going to geological disposal is calculated based on the MR_{xx} values and the respective loss factors in the different fuel cycle steps, depending on the fuel cycle scheme. These TRU-losses are then compared with the amount of TRUs going to repository for the LWR-OFC (scheme 1) and result in the RLOSS-parameter, where RLOSS is the normalised TRU loss to repository relative to the once-through LWR base-case scenario. In addition, the added cost of the NFC fuel cycle scheme (again, relative to the once-through LWR base-case scenario) in question divided by the amount of TRU not sent to repository (avoided through the P&T process) leads to an effective "marginal cost", MC($/kgTRU), that is also reported. As stated previously, all results are presented as comparative assessments for the improvement of each concept rather than as a competitive market selection.

Table 6.1. **Summary of technology parameters used to characterise each fuel cycle scheme**

Reactor technology	LWR-UOX	LWR-MOX*	Pu-burner	MA-burner (FR)	Fast reactor	TRU-burner (ADS)	MA-burner (ADS)
Fuel cycle scheme	1 to 4	2, 3c, 4	2, 4	3a	5	3b, 3c	4
Thermal power, P_{tH} (MWth)	4 240	4 240	3 600	1575	1 575	840	377
Net electric power, P_E (MWe)	1 450	1 450	1 450	600	600	275	119
Plant capacity factor	0.85	0.85	0.85	0.85	0.85	0.80	0.85
BU (GWd/tHM)	50	50	185	140	140	140	140
Burn-up fraction, BU_f	0.0514	0.0507	0.1842	0.143	0.143	0.143	0.143
Equivalent full power days (d)	1 325	1 325	1 320	1 550		870	1 241
Blanket breeding ratio, BR	0	0	0	0	1	0	0
Actinide core compositions							
HM core mass, M_C (tonne)	112.24	112.35	25.69	17.55	17.73	2.59	3.15
Initial HM mass, M_{HMi} (kg/TWhe)	2 394.1	2 394.01	559.25	786.34	794.47	508.92	888.599
U initial fraction, y_{RUi}	1	0.919	0.5557	0.6696	0.7644	0.0121	0.0462
Pu initial fraction, y_{Pui}	0	0.081	0.4443	0.2914	0.2287	0.8237	0.4042
MA initial fraction, y_{MAi}	0	0	0	0.03989	0.0069	0.1642	0.5496
Final HM mass, M_{HMf} (kg/TWhe)	2 270.8	2 267.4	456.2	675.2	691.9	382.2	755.5
U final fraction, y_{RUf}	0.9858	0.9361	0.5714	0.6978	0.7856	0.0161	0.0544
Pu final fraction, y_{Puf}	0.0127	0.0582	0.3953	0.2660	0.2068	0.8016	0.4759
MA final fraction, y_{MAf}	0.0016	0.0057	0.0334	0.0363	0.0077	0.1823	0.4697

* For non-homogeneous cores, e.g. MOX, these initial and final mass fraction pertain to the respective MOX core components (f_{MOX}); the remaining core fractions ($1-f_{MOX}$) are described by the LWR-UOX parameters.

6.2.2 Unit cost data-base

Unit costs[59] were allocated to each of the NFC steps described in Figure 6.1. As this analysis aims at charting cost trends that improve both economic and waste-toxicity performance for each of the technologies considered, rather than presenting a "best-estimate" result, a cost range (i.e. lower bound, nominal value, upper bound) was defined for each of these "top-level" (e.g. highly aggregated) fuel cycle steps. The nominal unit cost value generally refers to best available unit costs for the fuel-cycle or operation in question. This nominal value is based mainly on the results reported in the references, as well as on expert judgement, when necessary (e.g. repository costs, or cost of advanced pyro-chemical processing schemes). The upper bound for the unit costs is based on expert judgement by analysing the sensitivity of the nominal values to changes in technology performance, maturity of technology, economy of scale and other considerations. The same approach holds for the lower-bound unit-cost values that may be considered as the lowest envisaged cost for a given NFC step using the projected mature state of technology. Again, economies of scale, learning-curve effects and expert judgements were applied to derive these lower-bound values. As this costing task evolved, it was decided to use only the nominal cost database for the LWR technology, with each element of that data base being bounded by estimates of standard deviations (σ-values), rather than carrying along three databases per se (e.g. low, nominal, high). In this way, statistical analyses could be applied to a set (for each fuel cycle scheme) of relative costs, rather than having to deal with a range of cost databases wherein the basis or normalising cost was also varying. While "this nominal-plus-sigma" approach clarified the normalisation issue, it raises the problem of adopting σ-values for highly skewed unit cost parameters arises. Additionally, the desire to chart future actions on the basis of parametric systems analyses (PSA), while still retaining a normalisation metric, has potential to confuse when that normalising technology or fuel cycle scheme is also part of the PSA. In some cases, therefore, evaluations based on the variations of absolute costs proved to be clearer.

Tables 6.2 and 6.3 summarise the unit costs applied in the P&T cost analysis. These unit costs and related economic performance assumptions are discussed in the following sub-sections. It is emphasised that not all (detailed) fuel-cycle steps have been taken explicitly into account. Some costs related to interim stock between fuel-cycle steps were aggregated and incorporated into previous or subsequent fuel-cycle steps, whereas in other cases the costs were considered to be of less importance in the present scoping analysis (e.g. differences in cost for re-enrichment of irradiated uranium versus natural uranium, disposal of secondary wastes, etc.). In general, over the long term (i.e. beyond 20 years) the evolution of costs of industrial-scale processes is likely to follow the historic trends (i.e. decreasing in constant terms). The magnitude of such decreases, however, will depend on the vitality of the nuclear industry at both national and international levels, and the availability and sharing of operating experience that drives "learning-curve" cost reductions. Also, fuel-cycle cost comparisons need to take into account financial aspects, such as level of funding, R&D efforts, management of provisions and differences in discount rate (e.g. perceived risks associated with the development and application of a given technology). Depending on the special boundary conditions, NFC costs for individual countries and, in addition, for the individual utilities within a country, may deviate significantly from these generic figures. Regional and temporal differences in key technological and financial parameters, however, must be recognised in assessing the results of this normalised economic assessment that has a main goal of identifying technological improvement needed for each technology being studied, rather than providing a market-selection process/mechanism for the range of technologies being examined by this study.

All unit costs have been expressed in US dollars of 2000. An average annual escalation rate of 3%/y was applied to values based otherwise. An exchange rate of one euro per dollar was applied,

59. Or unit cost estimating relationships, CERs, in the form of $/We, $/kgHM, etc.

when needed, on the assumption that the markets would eventually reconcile present differences. Finally, a fixed charge rate[60] FCR for investments was applied, ranging from 8 to 14%/y with a nominal value of 10%/y. To FCR is added an annual charge rate f_{OM}(1/y) for all (fixed and variable, except for NFC-related charges treated separately), which are operations and maintenance (O&M) expenditures. Decontamination and decommissioning (D&D) charges are expressed by increasing FCR by a factor of $(1 + f_{DD})$ to reflect an additional annual charge being delivered to an D&D escrow fund.

Table 6.2. **Unit costs for nuclear fuel cycle (NFC) steps relating to LWRs**

Step	**Description**	**Unit cost** *Nominal value* *(±σ)*	**Unit***
UC_{MM}	Uranium mining and milling	30 (±*10)*	$/kgU
UC_{CV}	Uranium conversion from U_3O_8 to UF_6	5 (±*2)*	$/kgU
UC_{ER}	Uranium enrichment	80 (±*30)*	$/SWU
UC_{CV}'	Uranium conversion from irradiated UO_2 to UF_6	24 (±*5)*	$/kgU
UC_{FF}(UOX)	UOX fuel fabrication	250 (±*50)*	$/kgHM
UC_{Udepl}	Depleted uranium long-term storage	3.6 (±*1)*	$/kgU
UC_{CS}(SF)	Spent UOX-fuel interim storage (standard 2 years)	60 (±*10)*	$/kgHM
UC_{TR}(SF)	Spent fuel transport	50 (±*10)*	$/kgHM
UC_{PR}(UOX)	UOX reprocessing	800 (±*100)*	$/kgHM
UC_{FF}(MOX)	MOX fuel fabrication	1 100 (±*200)*	$/kgHM
UC_{PR}(MOX)	MOX fuel reprocessing	800 (±*100)*	$/kgHM
UC_{RP}(SF)	UOX spent fuel conditioning and disposal	210 000 (± *50 000)*	$/m^3
UC_{RP}(SF)	UOX spent fuel conditioning and disposal	210 000 (±*50 000)*	$/m^3
UC_{RP}(HLW)	Vitrified HLW conditioning and disposal	400 000 (±*50 000)*	$/m^3
CAP_{LWR}	Capital cost of advanced LWR	1 700 (±*100)*	$/kWe
f_{OM}(reactor)	O&M annual charge for reactor operation as fraction of capital cost	4	%/y
f_{OM}(FF)	O&M annual charge for fuel fabrication plants as fraction of (fabrication plant) capital cost	15	%/y
f_{OM}(PR)	O&M annual charge for reprocessing plants as fraction of capital cost	6	%/y

* All costs are expressed in 2000 dollars. Unit costs for other base-years were corrected using an escalation rate of 3%.

6.2.2.1 Fuel cycle steps related to LWRs

Table 6.2 gives an overview of the NFC steps that are supportive of LWRs, as well as those steps that are common to most of the fuel-cycle schemes under consideration in this study. The unit costs shown in Table 6.2 indicate the nominal values based on expert judgement and literature survey where the applicability (i.e. range) of these unit cost values will be detailed in the following paragraphs. The costs may be considered valid for the short-to-medium time frame (i.e. up to the period 2010-2020). As noted previously, the multiple-database approach adopted for this study (e.g. three CDBs designated as low, nominal, and high) for the LWR-based technologies has been replaced by a single

60. The factor that gives equal annual payments for a total investment cost based in turn on interest during construction of a given construction time, debt-to-equity ratios, escalation rate, interest rate, and plant life.

(nominal) cost database and associated standard deviations (σ values), albeit the statistics of the associated cost distributions usually does not warrant the use of such exact statistical terms.

The cost of natural-uranium mining and milling has been relatively low over the past years, and no significant increase in uranium cost is foreseen in the next decade [168]. Significant uranium resources are available, and new primary resources may be found once (if) uranium demand rises again. Conventional uranium resources are estimated at around 4 million tU (Known Conventional Resources, KCR) that are recoverable at costs ≤130$/kgU. Reasonably Assured Resources (RAR), recoverable at costs of ≤130$/kgU[61], account for 2.3 million tU [169]. The conventional resources alone could sustain present-day nuclear power (once-through) capacity for at least the next 100 years, without significant increase in the cost of energy due to fuel charges. Besides conventional resources, large (unproven) resources of uranium exist. Phosphates are known to contain significant amounts of uranium and another practically inexhaustible potential source of uranium is seawater. The availability of these resources and the possible continuous downward pressure on natural uranium prices lead to an expected cost range of 20 $/kgU up to 80 $/kgU. The lower bound may apply if a buyers' market continues, but such low values would not represent a sustainable price, since a significant number of uranium mines would become uneconomical. The upper bound of 80 $/kgU may apply if a resurgence of nuclear energy increases the uranium demand, with the exploration and mining of new primary resources lagging behind.

The potential availability of an essentially unlimited supply of natural uranium (not to mention at least four times the energy resource in the form of thorium) has significant implications for the waste-disposal and P&T options being considered for the back-end of any expanding nuclear fuel cycle that might utilise such enormous resources at moderate costs. In fact, the P&T issue addressed by this study can be divided in economic, administrative, ecologically and social terms into plutonium management (PUM, mainly an economic and proliferation issue) and minor actinide management (MAM, mainly an ecological and biological hazard issue of longer range). While not part of this study or the associated economic analyses, the separation of the overall problem into PUM versus MAM issues cannot be ignored, even if emerging as key conclusions and recommendations for future work from the present study.

Because of the increasing impact of several market mechanisms (i.e. evolution from an inventory-driven market to a production-driven market, over-capacity in uranium enrichment plants, and the possible introduction of a uranium tail re-enrichment market), developments in conversion and enrichment are oriented mainly towards cost-reduction. It is hoped that in the long-term new facilities, based on advanced processes, could achieve enrichment costs of about 50 $/SWU. The nominal cost indicated in Table 6.2, therefore, can be considered valid for the foreseeable future as sufficient capacity for conversion and enrichment is available and new plants will have to operate in a competitive market where the cost of the service is the primary driver [168]. A lower bound of 50 $/SWU and a higher bound of 120 $/SWU are believed to cover the credible span of costs in the future. The range of costs for conversion from U_3O_8 to UF_6 is 3-8 $/kgU.

A cost indication of 18 $/kgU (1987 $) (i.e. 24 $/kgU and ranging from 15 to 30 $/kgU for the re-conversion of UO_2 coming from reprocessing of UO_2 (UOX) to UF_6 for re-enrichment purposes was given in [170]. In most cases, however, these re-conversion costs are avoided by using depleted uranium or natural uranium for MOX-fabrication, and any costs of conversion to oxide are assumed to be included either in the reprocessing or the fabrication costs [171].

61. Note that an increase of in the price of natural uranium to 130 $/kgU, five times the current price, would only increase the forward cost of nuclear energy by 20%.

The (cumulative) cost for storage of depleted uranium depends on whether the depleted uranium stock is managed as UF_6 or as U_3O_8, which require different processes and therefore have different cost structures. Based on [172], an indicative cost range was derived (i.e. 0.7 to 5.4 $/kgU) covering the long-term storage of depleted uranium in U_3O_8 form in vaults, as well as in UF_6 form in cylinders (although eventually, this UF_6 must be converted back to oxide).

The costs for interim storage of spent UOX-fuel were also reported in [159,170,173], ranging from 40 to 80 $/kgU, where an interim storage time of two years is standard. Reference [171] also reports a cost for "away-from-reactor" wet storage of LWR fuel assemblies (in 1987 $) to be a fixed 50 $/kgHM plus $5 \times T$ $/kgHM within a range of plus or minus 50%, where T(y) is the period of storage. Spent-fuel transport costs have been reported in many publications and amount about 50 $/kgHM (40-60 $/kgHM).

Separated plutonium storage and purification costs were reported in [171], where a range from 1 000 to 2 000 $/kgPu/y was judged to be relevant. The cost of purification from americium would be 18 $/g$Pu_{tot}$ (1987 $) ranging from 10 to 28 $/g$Pu_{tot}$, for plants treating about 2 tonnes Pu_{tot} per annum.

Existing over-capacities in a highly competitive market have led to a significant decrease in the UOX-fabrication price, which presently is in a range between 200 and 350 $ /kgU [168]. With respect to the future development of the UOX-fabrication price, the most important factors are technical developments influencing the fuel-assembly demand (e.g. burn-up increases from the nominal 50 MWd/t to values approaching 100 MWd/t), continued efforts to improve further the efficiency of the manufacturing processes, as well as effects resulting from mergers of suppliers (e.g. reduction of excess capacities, formation of cartels). The same considerations apply for MOX fabrication, ranging from 600 to 1 750 $/kgHM, where a traditional factor of four in the cost of MOX versus UOX fabrication remains valid. The situation concerning reprocessing is different than for fuel fabrication, since this market is characterised by only two main commercial entities with a strong reliance on long-term contracts with certain utilities. New contracts making use of existing facilities indicate significant price reductions are possible as a result of the accumulated experience, as well as reflecting the fact that much of the investment costs have been amortised already. In the future, new plants would benefit greatly from the extensive experience gained during the last decades, thereby allowing to simplify the plants, decrease their size and reduce maintenance requirements. Unit costs for LWR-UOX reprocessing (i.e. from 500 to 1 100 $/kgHM) were based on reported contract prices and assumptions made in other studies [168,174]. The cost for MOX reprocessing (i.e. same range and nominal value as for UOX-reprocessing) is valid as long as the MOX fuel can be mixed with UOX-fuel (i.e. fraction of MOX-fuel remains limited to 20 to 30% in a batch of fuel to be reprocessed).

The conditioning and geological disposal of high-level waste (vitrified or direct spent fuel) is not yet based on industrial experience, and most quoted costs rely on estimates and detailed design studies made in the different member countries under differing assumptions and political and legal circumstances. As the geological conditions and amounts of waste differ according to national nuclear energy programmes, the cost ranges are wide, as are the specific long-term properties of repository containment (e.g. relative importance and time-scale of actinide versus LLFP releases to the accessible environment). Important technical factors that affect costs are the size of the system, time schedule of the disposal project, geological medium (particularly the presence and relative location of water and whether the environment is oxidising), and (to a lesser extent) the engineered-barrier system chosen. Next to these technical factors, social and political issues related to the degree to which the future is discounted and equity of future generations is valued also affect these disposition costs. Lastly, the relative importance of fixed and variable repository costs differs from location to location and has a strong impact on the scaling of unit cost (e.g. $/kgHM) with repository size. These factors will affect the siting and licensing process as well as the overall waste management policy [173]. Studies show the variability of normalised (disposal)

costs depending on the size of the system and the waste management policy. Recent studies in Belgium have indicated that previous estimates can be significantly reduced. Disposal costs are estimated to be 0.2 M$/m^3 or less for spent UOX fuel, and about 0.5-0.7 M$/m^3 for HLW [175,176]. It is also important to consider that the volume of HLW conditioned in glass is about four to ten times lower than the equivalent spent fuel in a metallic canister. Where the conditioning of 1 tonne spent fuel in a once-through fuel cycle scheme results in 2 m^3 of conditioned spent fuel for disposal, only 0.115 to 0.465 m^3 of conditioned vitrified HLW waste arises in a reprocessing fuel cycle scheme.[62] A canister of vitrified waste (volume 0.18 m^3, weight 492 kg) typically contains 47.6 kg of fission products and 3.55 kg of actinides (as oxides) [22]. The rest of the container consists of carrier glass (i.e. 94.3 kg) and the container itself (80 kg). The cost has been expressed in $/m^3 units, since this unit has been widely used in most of the repository design studies. The cost includes only the direct cost associated with waste packaging and disposal, and do not include the costs of R&D, site screening and evaluation, and waste transportation outside the repository site. As this study focuses on steady-state equilibrium situations, the exclusion of these latter costs is appropriate, but the question remains as to who pays for the siting, qualification, and construction of the repository. Over the past five to ten years, new cost assessment studies shave been published in several of the Member countries indicating that the proposed unit cost in Table 6.2 remain valid and may range from 100 000 to 500 000 $/m^3 for spent fuel disposal and from 100 000 to 700 000 $/m^3 for vitrified waste disposal. Certain countries, however, have published significantly higher estimates (e.g. spent fuel disposal in Switzerland [167]).

In this cost analysis, it has been assumed that the disposal costs for vitrified waste arising in the fuel cycle schemes 2 to 5 are proportional to the amount of fission products produced. As mentioned above, a glass canister is essentially loaded with fission products, which define the thermal loading and, therefore, the design of the repository according to present practice. As was shown in Chapter 3, an average amount of 118 kg fission products is produced per TWhe. These waste products would result, on average, in 2.5 waste canisters per TWhe, thereby indicating a conditioning and disposal cost of 180 000 $/TWhe (= 0.18 mill/kWh) that is independent of the fuel-cycle scheme. Since these costs are only a small part of the total generation cost for nuclear energy (on average about 0.5% of generating cost of electricity at 5% discount rate), any reduction of disposal costs attributed to P&T may be considered as having limited impact on the overall cost of electricity.

The unit capital costs (i.e. overnight construction costs including owner's cost) for advanced LWRs were reported in [162] and confirmed during the past years in other studies. These unit (total) capital costs may range from UTC = 1 400 up to 2 200 $/kWe depending on the specific licensing situation in Member countries and local variations in materials and labour costs. Fixed operation and maintenance costs amount to about 65 ± 25 $/kWe/y, or about f_{OM} = 4%/y of the original (total) capital cost. Non-discounted decommissioning costs for LWRs account for about f_{DD} = 8% of the initial (total) capital cost; these D&D costs become negligible when escrowed in a discounted account, with the factor f_{DD} being applied here as an effective increase in FCR to account for such funds being set aside. Interests during construction need also to be taken into account in order to arrive at investment costs and to derive costs of electricity. An average construction time of six years may be envisaged with construction costs split in the proportions of 10%, 15%, 25%, 25%, 20% and 5% between successive years. These ground rules, together with assumptions on debt-to-equity ratios, interest rates, and escalation rates, lead to a fixed charge rate in the range FCR = 0.08-0.14 1/y, with FCR = 0.10 1/y

62. The HLW arising in reprocessing amounts to 0.115 m^3 per tonne of spent fuel, where an additional 0.35 m^3 of ILW arises which is mostly conditioned in the HLW glass matrix. Generally, in the HLW and spent-fuel disposal costs listed in Table 6.2, which are given in terms of unit volume of waste package, a "density" conversion factor is taken as 8.70 tHM/m^3 or 0.50 tonneHM/m^3, respectively. Hence, for the corresponding volume-based unit costs listed in Table 7.1, the weight-based costs of SNF and HLW disposal amount to 420 and 46 $/kgHM, respectively.

being adopted for the nominal value. Hence, for the once-through LWR case of UTC = 1 700 $/kWe, the cost of electricity associated with capital, fixed O&M and D&D charges amounts to $[FCR(1. + f_{DD}) + f_{OM}]UTC/(1 - \varepsilon)/ pf/(8\,760) \times 10^6 = 34.5$ mill/kWh, where the re-circulating power fraction is taken as $\varepsilon = 0.02$ and the plant capacity factor is $p_f = 0.85$. Addition of variable O&M costs push this base-case or normalising value up to ~38-40 mill/kWh.

The annual charges for O&M for reactors (2-5%/y), fabrication (10-25%/y) and reprocessing plants (4-10%/y) are in agreement with today's practice, where no significant changes are expected for new plants or technologies. In fact, higher O&M charges may be expected for advanced fabrication and even advanced processing plants as the control on criticality, safety, working with thermally and radioactively "hotter" fuels, and the implementation of non-proliferation measures may become more stringent. It has been reported that different control measures by international organisations in present-day MOX-fabrication plants represent about 15% of the MOX-fabrication cost [177], above and beyond the costs of maintaining such international organisations, per se. Generally, these O&M (and FCR) factors for fuel-fabrication and processing charges are not used directly in the cost estimates, since the unit costs are expressed in $/kgHM units and already incorporate these plant-related financial and operational factors

6.2.2.2 Advanced fuel cycle step unit costs

The assessment of the costs for the advanced NFC steps is based primarily on a literature survey and in some instances on expert judgement. Table 6.3 summarises the unit costs that will be detailed in this section.

Capital cost of FR plant

The basis for the unit cost assessment is the EFR reactor, as designed by Framatome [178], and the S-PRISM design by GE [179]. Information from SuperPhénix [177] and Monju [180] were included as well as results of the studies performed by ORNL in the 1980s and 1990s [159,180,182]. All the FR-plants considered with MOX-fuel were based on sodium-cooled technology.

The Oak Ridge National Laboratory (ORNL) performed in the 1980s and 1990s several studies related to the technology and economics of ALMR Deployment fuel cycle schemes [159,181,182]. In these assessments, a MOX-fuelled ALMR of 1 488-MWe(net) capacity and 86% capacity factor was considered. The economic analysis in [159] reports an initial investment cost (base construction cost) of 2 825 $million (UTC = 1.90 $/We) for a first commercial plant (with an annual O&M cost of 113.3 $million/y, or $f_{OM} = 4.0$%/y) where an n^{th}-of-a-kind plant would have an initial investment of 2 413 $million (UTC = 1.62 $/We) and an annual O&M cost of 89.6 $million/year ($f_{OM} = 3.7$%/y, all 1992-$).

The EFR-studies indicated a capital cost for a EFR plant some 20-30% higher than for LWRs [178] for a first-of-a-kind plant where n^{th}-of-a-kind plant would only be marginally more costly than LWRs. JNC (Japan) indicates a current capital cost for FR-MOX systems of 4 700 $/kWe, where the future target cost should become 1 700 $/kWe [180].

In 1995, RAND Corporation reported a plant capital cost of 2 760 $/kWe (1987 $). In addition, a range of 1 300-1 800 $/kgHM was suggested for the FR-MOX fabrication and a range of 1 440-1 800 $/kgHM was given for the reprocessing of this fuel [183].

Table 6.3. **Unit costs for advanced nuclear fuel cycle (NFC) technologies**

Step	Description	Unit cost			Unit*
		Lower bound ''lo''	*Nominal value ''nm''*	*Upper bound ''hi''*	
FR with MOX-fuels					
$CAP_{FR\text{-}MOX}$	Capital cost for FR-MOX reactor	1 850	2 100	2 600	$/kWe
UC_{FF}(FR-MOX driver)	FR-MOX driver fuel fabrication	650	1 400	2 500	$/kgHM
UC_{FF}(FR-MOXblanket)	FR-MOX blanket fuel fabrication	350	500	700	$/kgHM
UC_{PR}(FR-MOXdriver)	FR-MOX driver fuel reprocessing	1 000	2 000	2 500	$/kgHM
UC_{PR}(FR-MOXblanket)	FR-MOX blanket fuel reprocessing	900	1 500	2 500	$/kgHM
FR TRU burner					
$CAP_{FR\text{-}TRU}$	Capital cost for FR-TRU burner	1 850	2 100	2 600	$/kWe
UC_{FF}(FR-TRU)	FR-TRU fuel fabrication	1 400	2 600	5 000	$/kgHM
UC_{PR}(FR-TRU)	FR-TRU fuel reprocessing	1 000	2 000	2 500	$/kgHM
All FR					
CAP_{FR}	Capital cost for FR	1 850	2 100	2 600	$/kWe
UC_{FF}(FR_driver)	FR driver fuel fabrication	1 400	2 600	5 000	$/kgHM
UC_{FF}(FR_blanket)	FR blanket fuel fabrication	350	500	700	$/kgHM
UC_{PR}(FR_driver)	FR driver fuel reprocessing[63]	1 000	2 000	2 500	$/kgHM
UC_{PR}(FR_blanket)	FR blanket fuel reprocessing	1 000	2 000	2 500	$/kgHM
ADS TRU burner					
$CAP_{ADS\text{-}TRU}$	Capital cost ADS-TRU burner (excl. target and accelerator)	1 850	2 100	2 600	$/kWe
UC_{FF}(ADS-TRU)	ADS-TRU fuel fabrication	5 000	11 000	15 000	$/kgHM
UC_{PR}(ADS-TRU)	ADS-TRU fuel reprocessing	5 000	7 000	18 000	$/kgHM
ADS MA-burner					
$CAP_{ADS\text{-}MA}$	Capital cost for ADS-MA burner (excl. target and accelerator)	1 850	2 100	2 600	$/kWe
UC_{FF}(ADS-MA)	ADS-MA fuel fabrication	5 000	11 000	15 000	$/kgHM
UC_{PR}(ADS-MA)	ADS-MA fuel reprocessing	5 000	7 000	18 000	$/kgHM
Other					
UC_{beam}	Accelerator cost (incl. target)	5	15	20	$/$W_{beam}$

* All costs are expressed in 2000 dollars. Unit costs for other base-years were corrected using an escalation rate of 3%.

S-PRISM (i.e. 1 520 MWe, 93% capacity factor) was estimated to cost 2 200 M$ (1996 $) (i.e. 1 450 $/kWe (2000 $) [179]). Annual O&M costs were calculated as 76.28 M$/y ($f_{OM}$ = 3.5%/y). The same reference for S-PRISM may be used for this type of FR with metal fuel loading. Comparable information is available from the IFR programme (ANL).

The capital cost values listed in Table 6.3 are given in terms of base construction costs using these references, where the lower, nominal and upper bound capital cost values for FR are higher than the nominal capital cost of an ALWR by +10%, +25% and +50% respectively. The decommissioning costs, interest during construction and O&M- costs for FRs may be taken based on the same assumptions as for LWRs (e.g. same construction period and cost schedule). Unlike Table 6.2, the three databases (low, nominal, and high) were retained because of the skewed nature of the uncertainties, with the "high" value further than the "low" from the "nominal".

63. Blanket and driver fuels are considered to be co-reprocessed as a step towards reducing proliferation propensity.

Capital cost of ADS plants

The main reference used to assess the capital cost for ADS-TRU/MA burning systems is the ATW-Roadmap exercise [8]. The ALMR was considered as a reasonable cost basis for the ATW cost assessment. Modifications to the ALMR design are needed and were in some respects detailed in the ATW-Roadmap document.

The capital cost of an ADS has been divided into two parts, respectively for the accelerator and target (ACC) and for reactor and power-conversion (Rest of Plant, ROP). This latter part includes core, vessel, balance of plant, etc. but excludes fuel-fabrication (FF) and processing (PR) plants, since both the capital and O&M annual charges incurred for the latter two items are expressed on a per-kgHM basis, which includes both capital and O&M charges. This separation of ACC and ROP cost accounts implies that no cost benefit has been attributed to the possible elimination of, for instance, control rods. It was perceived within the context of this cost analysis that possible cost reductions may be offset by cost increases related to complications in containment and other systems.

The basic construction cost for an ADS was therefore set equal to that for a FR with an addition to cover capital costs of accelerator and target. Generally, the target accounts for only a few percent of the total accelerator costs, so at the level of the present costing model, it matters little whether it is included with the blanket or the accelerator. At the highly aggregated level of this analysis, the accelerator cost is estimated on the basis of proton beam power, using unit costs in the range UC_{beam} = 5-20 \$/W_{beam}, with the ATW Roadmap Study [8] giving values close to the upper limit. The costing model [163] developed and used for this study also examines the trade-off between accelerator and material-handling (e.g. fuel-fabrication and processing) where, as in TRU-burning ADSs, reactivity swings are large and the accelerator is sized to maintain a constant fission power over the burn cycle: short batch times lead to a reduced reactivity swing and so to reduced accelerator size, but more mass-handling. Lastly, the cost of added power required to drive the accelerator was accounted through the increased ROP needed to supply that re-circulating power rather than charging for external purchases at some exogenous market price.

The cost of beam (and target) has been based on recent technology assessments [167,8,9,183,184] for accelerators in the power range (beam energy and intensity) of the ADS systems considered in this study. It cannot be over-emphasised that the aggregation of all accelerator costs into a parameter like UC_{beam}(\$/W_{beam}), besides offending accelerator physicists, represents something of an oversimplification in ignoring the possible discovery of some options for reducing both capital and operating costs in this large account. More complete and detailed accelerator models must eventually be used [165].

FR and ADS fuel treatment

Metal or nitride fuels have not yet been fabricated or reprocessed on a semi-industrial scale. Only laboratory- or pilot-plant scale experience exists, for instance in treating EBR-II fuel in the Fuel Conditioning Facility (FCF) by the electro-metallurgical process developed by ANL [185]. Information on these fuel treatment processes is therefore limited and mainly based on conceptual technology assessment studies.

The ATW-roadmap [8] studied the fuel-treatment process in detail and reported [186] unit costs for the processes involved. Other references include the MIT report [187], where a comparison with advanced breeder reactor fuel was mentioned, and the recent DOE report on electro-metallurgical treatment of EBR-II spent fuel [185].

Fuel fabrication costs for the ATW project were reported to be around 11 300 \$/kgTRU (1999-\$) for an nth-of-a-kind plant. This unit cost corresponds to about 2 800 \$/kgFM. The other references were based on the same or comparable assumptions and therefore arrived at the same values.

Experience in fabricating LWR-MOX and FR-MOX fuel suggested a cost increase by a factor of about 5 to 10, since the presence of significant quantities of the minor actinides (particularly the high-activity alpha-emitting americium and plutonium isotopes as well as neutron-emitting curium) demands a new design for fuel fabrication plants to allow for remote handling and criticality concerns. Whereas present-day fuel-fabrication plants can use glove-box handling in almost all of the fabrication steps, these new plants for highly active fuel would require shielded cells and disperse substantial levels of decay heating. In addition, added care must be taken to prevent criticality, and the higher neutron source strengths demand additional shielding. The presence of ^{238}Pu and highly active isotopes of americium and curium in fabrication is, therefore, the most important parameter in assessing the cost of fabrication [177] of these fuels.

Experience in handling fuels containing americium lends greater credence to extrapolations of the costs for fabricating them. This is not true of curium-containing fuels. The unit costs listed in Table 6.3 are based on the available information and take account of the shielding requirements in fabrication. It should be mentioned that all assessment studies of advanced fabrication plants do account for a similar or even higher annual O&M-cost (i.e. 20-25%/y, compared to present-day (UOX and MOX) fabrication plants.

The driver and blanket fuel for FRs are considered to be co-processed, although a difference in fabrication cost has been included to reflect the significant difference in fuel composition. The value for fabricating metallic blanket has been assumed comparable with that for FR-MOX blanket fuel, since no specific cost differences are expected between oxide and metallic uranium fuel.

Despite the difference in specific heat load and annual throughput for the TRU- or MA-fuel fabrication plants in schemes 3a and 4, the same unit cost for fabrication was applied. These fuel fabrication costs would essentially be defined by the throughput of curium.

For fuel reprocessing, the increase by a factor of ten in unit costs was judged to be reasonable, since the composition of the fuel, the size of the reprocessing plants (i.e. throughput), and the technology to be applied are all significantly different from present-day practice, with some exception for the (smaller scale) treatment of EBR-II fuel [185]. Unit costs for reprocessing ranging from 6 000 to 20 000 $/kgHM were derived in references [184-187]. The recent report on EBR-II fuel reprocessing suggests an operational cost of about 15 000 $/kgHM (average value for treating driver and essentially depleted uranium blanket fuel) using the existing Fuel Conditioning Facility at ANL-West [185]. Assuming a new plant using the same electro-metallurgical process, and considering that the annual O&M cost fraction remains about 5-6%/y of the initial investment, the full unit cost for fuel reprocessing lies in the range 19 000-24 000 $/kgHM. This value has been chosen as upper bound for the future pyro-process to be applied in the ADS-schemes, without taking account of economies-of-scale, learning effects and technological improvements. Based on this experience, the Expert Group selected an upper bound of 18 000 $/kgHM as appropriate in the long-term. Despite the difference in specific heat loads and the differences in required throughput of the reprocessing plants, it has been assumed that these two factors compensate each other for the TRU-burning and MA-burning cases, and, therefore, the same unit costs are proposed for the fuel cycle schemes 3a and 4.

The HLW arising from electro-metallurgical processes is composed of two forms, ceramic and metal. The bulk of the fission products and transuranic elements are incorporated into the ceramic, which is a glass-bonded sodalite monolith. The metal contains fuel cladding, the remainder of the fission products, and trace amounts of uranium [185]. Based on Reference [185], a unit cost for disposal of these waste forms would amount to about 400 $/kgHM (net present value cost; the cost for disposing a canister of HLW in a geologic repository was estimated to be $475 000). The latter disposal cost was assumed to cover also this kind of HLW waste from the electro-metallurgical process, as would make the value accord with Table 6.2 and the assumption on HLW-cost mentioned above.

6.3 Results

The results of the cost analyses divide into two parts:

- The relative cost and TRU loss to repository according to the data largely summarised in Tables 6.1-6.3 and designated the Point-of-departure (POD) case.
- The impact of single-point parameter variations or departures from that POD case designated as Parametric Systems Analyses (PSA).

The following two sub-sections present these results accordingly.

6.3.1 Point-of-departure case

The aggregated, relative costing and (TRU) loss to repository results, as embodied in the ratios RCOST = COE(nsc)/COE(1) and RLOSS = $LOSS_{TRU}$(nsc)/$LOSS_{TRU}$(1), are summarised in Table 6.4 for the seven fuel cycle schemes considered by this study.[64] Figures 6.3 and 6.4 present parts of Table 6.4 in graphical form to facilitate cost comparison between fuel cycle schemes (Figure 6.3) and the cost-versus-loss trade-offs (Figure 6.4).

The main message from these results is that reduced TRU losses to repository imply an increased overall system cost of electricity, and that certain combinations of technologies cost more than others on the cost data assumed. Furthermore, those fuel-cycle schemes that use more expensive technologies (e.g. ADS-based) show an overall economic benefit in burning as much plutonium as is possible in more conventional systems such as MOX-LWRs and MOX-FRs.

The marginal cost results show that the cost of avoiding disposing of TRUs remains modest for schemes 2, 3a and 4; it amounts to about 30-40% of the conditioning and disposal cost for 1 kg of HM as vitrified HLW.

A comparison of the LOSS values in Table 6.4 with the HLW production values in Table 3.3 shows that the precision of the combined cost and mass balance model is limited. However, this limitation has to be balanced against the simplicity of the model which allows e.g. parametric systems analyses to be carried out easily.

Table 6.4. **Aggregated costing and TRU-loss (to repository) results for the Base or Point-of-departure case**

Fuel cycle scheme (nsc)	**1**	**2**	**3a**	**3b**	**3c**	**4**	**5**
U-loss (kgU/TWhe)	2 299.23	1.77	1.45	1.86	2.09	1.67	4.65
Pu-loss (kgPu/TWhe)	29.53	0.1	0.10	0.16	0.16	0.12	0.26
MA-loss (kgMA/TWhe)	3.66	9.47	0.01	0.03	0.03	0.03	0.005
TRU-loss (kgTRU/TWhe)	33.19	9.57	0.12	0.19	0.18	0.16	0.26
RLOSS	*1*	*0.2883*	*0.0035*	*0.0057*	*0.0055*	*0.0047*	*0.008*
COE (mill/kWh)	38.02	40.70	42.41	53.48	49.44	44.16	56.86
RCOST	*1*	*1.07*	*1.12*	*1.41*	*1.30*	*1.16*	*1.50*
Marginal cost MC (‘000 $/kgTRU)		113	133	468	346	186	572

64. In the remaining of this chapter, “nsc” will indicate the fuel cycle scheme number, e.g. nsc = 2 refers to the fuel cycle scheme 2.

Figure 6.3a. **Comparisons of relative fuel cycle scheme costs to the Base or POD case. (UC_{beam} = 15 \$/W_{beam}; BU(LWR) = 50 GWd/tHM; nominal unit cost values)**[65,66]

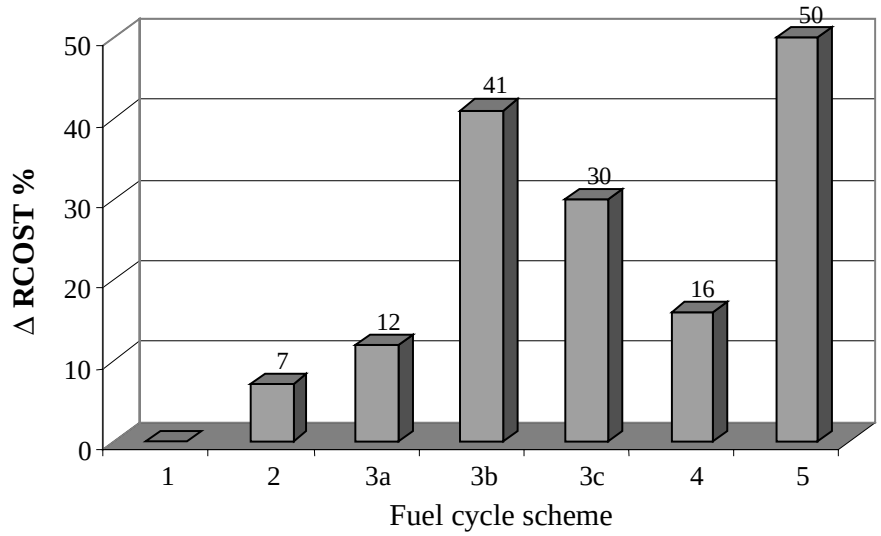
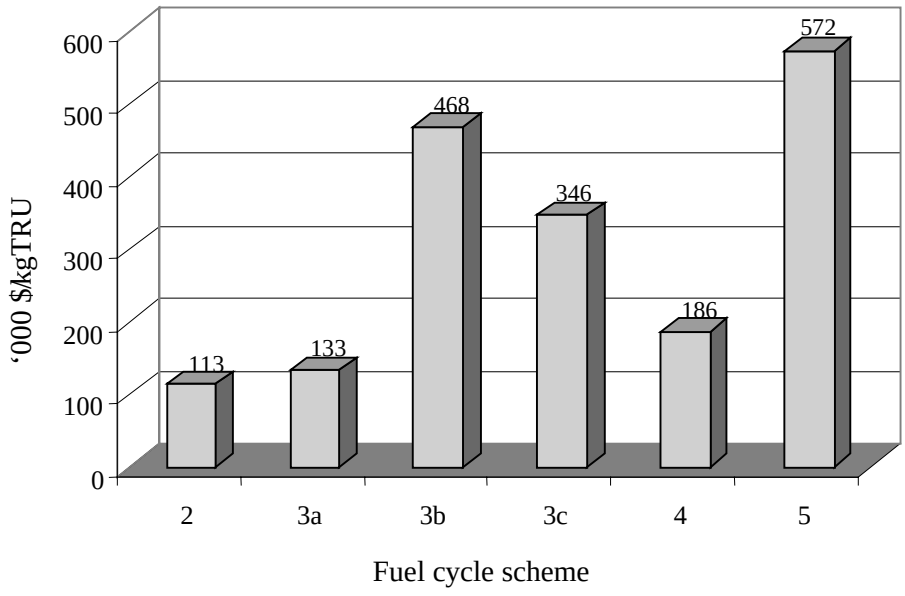
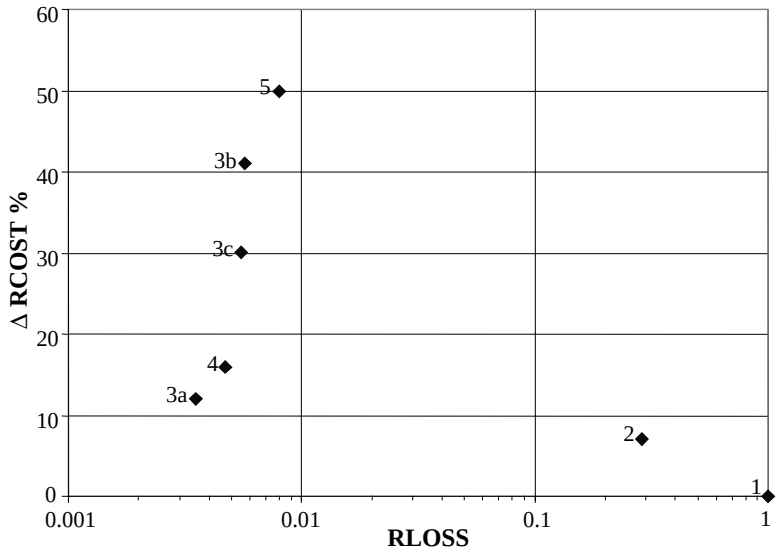


Figure 6.3b. **Marginal cost MC ('000 \$/kgTRU)**[67]



65. ΔRCOST = (RCOST - 1) × 100.
66. The fast reactor model used in this study was optimised for burning (scheme 3a) and had a high surface to volume ratio to promote leakage. Converting it to fissile self-sufficiency required more blanket mass flow than would be the case when the core is originally designed as a low surface to volume breeder; the resultant cost of blanket recycle shown here therefore is an upper bound.
67. MC = [COE(nsc) - COE(1))/(LOSS(nsc) - LOSS(1)].

Figure 6.4. **Comparisons of costs fuel cycle scheme and TRU loss trade-offs with the Base or POD case. (UC_{beam} = 15 \$/W_{beam}; BU(LWR) = 50 GWd/tHM; nominal unit cost values)**



6.3.2 Parametric system analysis

In spite of the simplicity of this highly aggregated, equilibrium nuclear fuel cycle model and the aggregated unit costs used to convert the resulting mass flows and inventories into annual charges, the number of economic and technological parameters is large. Since varying all these parameters is both counterproductive (diffusive) and impracticable, it was decided to vary predominantly those parameters that might improve some of the more costly concepts. Therefore, accelerator cost for ADS-based fuel cycle schemes and fuel burn-up in the driver LWR technology were identified as relevant subjects for these PSAs. Before embarking on these single parametric cost variations, the impacts of the higher-level parameters like unit cost base per se and the burn-up fraction, BU_f, for systems with fully closed fuel cycles are reported.

6.3.2.1 Cost data base variation

The uncertainty in the CDB listed in Tables 6.2 and 6.3 is expressed in two forms: standard deviations (σ-values) for the more developed technologies (Table 6.2); and specific upper ("hi") and lower ("lo") bounds placed on unit costs relative to the "nominal" ("nm") or base-case values (Table 6.3). It can be seen that some of the uncertainties are large. First, emphasis is placed on examining the impact of the cost ranges associated with the advanced technologies (Table 6.3). Figure 6.5 compares the percentage change in relative costs ΔRCOST for each fuel cycle scheme as the cost database (CDB) is changed. According to the structure represented in Tables 6.2 and 6.3, the normalising LWR-OFC cost remains unchanged as the different CDBs are selected. While the cost ordering of fuel cycle schemes remains unaltered as CDB is changed, movement away from the nominal cost base case, CDB(nm), in either "hi" or "lo" directions changes in these relative costs by a factor of about two.

Figure 6.6 shows the correlation of ΔRCOST plotted versus RLOSS for schemes 2, 3a, 3b, 3c and 4. The primary conclusions from these comparisons are that the cost sensitivity over the CDB range embodied in Table 6.3 is large, but the RCOST ordering of the schemes remains the same as for the

POD, and that the economic advantage of pre-burning as much plutonium as possible in less expensive technologies is hence re-confirmed; this ordering is not affected by the choice of CDB.

It must be noted, however, that these results were obtained under the assumption that all low or upper bound values would occur simultaneously for each cost account, and the realism of achieving such an absolute bound is open to question.

Figure 6.5. **Impact of unit cost ranges for advanced-technology costs as reflected in Table 6.3 on the relative costs associated with each fuel cycle scheme**

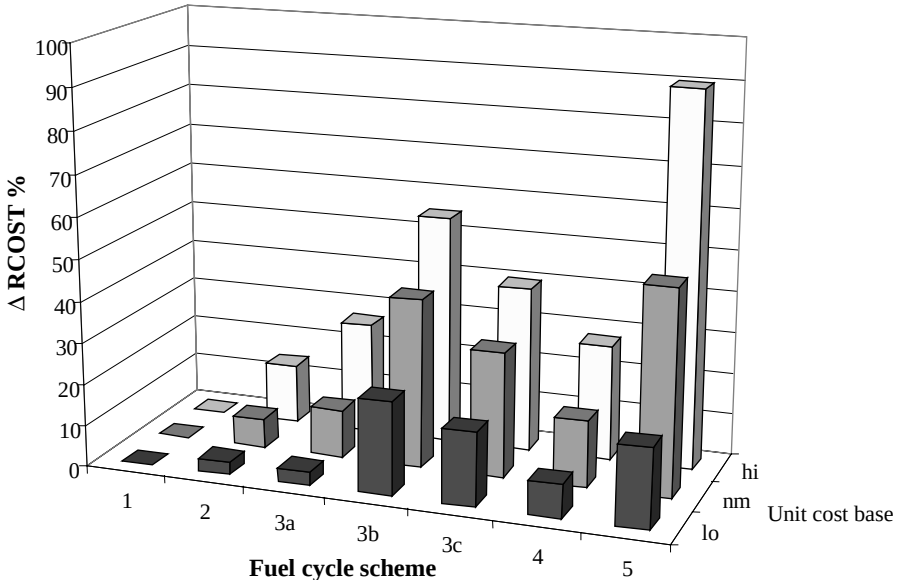
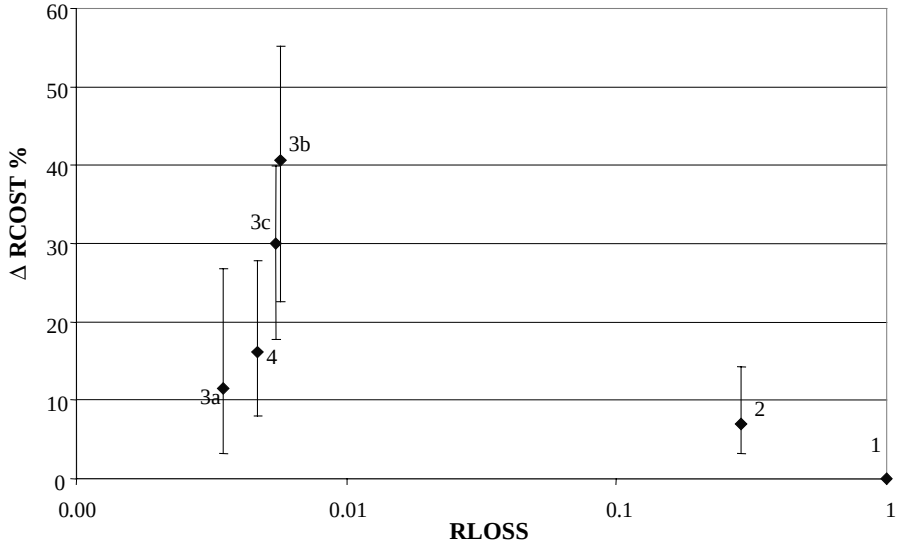


Figure 6.6. **Comparisons of fuel cycle scheme costs and TRU-loss trade-offs (BU(LWR) = 50 GWd/t), with the range for each point (scenario) being determined by the cost-data-base selection CDB (lo, nm, hi)**



6.3.2.2 Burn-up fraction variation for systems with fully closed fuel cycle

The equilibrium mass-balance, aggregated-costing model has been used to perform single-point parametric studies. A crucial parameter in this regard is the per-pass burn-up fraction, BU_f, for the fully closed fuel cycle schemes 3a, 3b, 3c, 4 and 5. Figure 6.7 shows the variation in both RCOST and RLOSS as BU_f for the systems with fully closed fuel cycles is varied. Both cost and loss seem to saturate at or above the POD value of $BU_f = 0.14$, but both increase rapidly as burn-up fractions fall below $BU_f = 0.05$. The lower burn-up fraction results in a steep increase in the number of recycles needed to transmute a certain amount of TRUs, and, therefore, each recycle pass adds to losses in reprocessing and fabrication as well as to the costs for these processes. For high burn-up fractions, the number of recycling iterations becomes smaller and the cumulative effect of losses-per-cycle saturates to a lower value.

As in scheme 4 only the small, second stratum mass flows are affected by the parameter variation, the RCOST and RLOSS values saturate at lower burn-up fractions per pass than in the other schemes. This result confirms again the overall economic benefit from pre-burning plutonium in lower-technology systems to the maximum extent possible.

Figure 6.7. **Relative (TRU to repository) loss, RLOSS, and dependence of relative cost, RCOST, on burn-up fraction, BU_f, for the fully closed fuel cycle schemes (3a, 3b, 3c, 4, 5) for otherwise POD parameters**

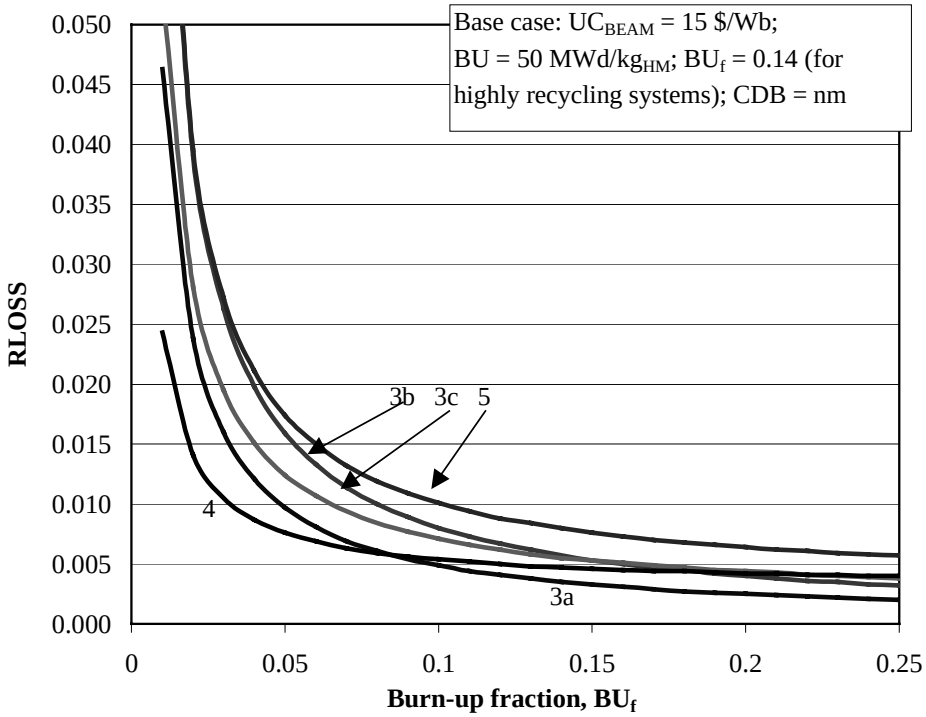
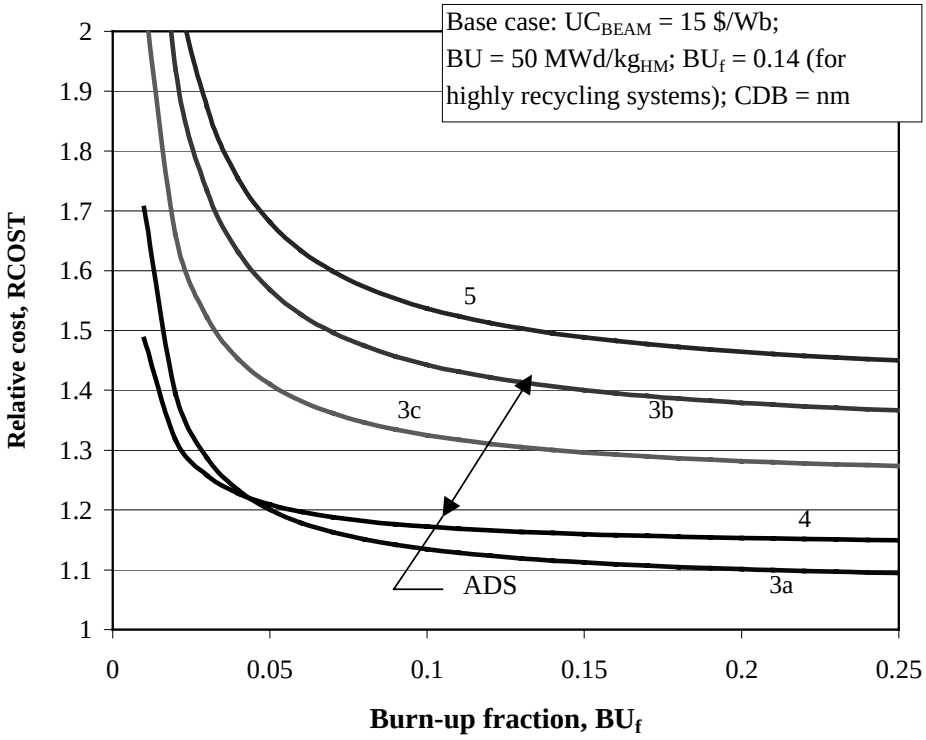


Figure 6.7. **Relative (TRU to repository) loss, RLOSS, and dependence of relative cost, RCOST, on burn-up fraction, BU_f, for the fully closed fuel cycle schemes (3a, 3b, 3c, 4, 5) for otherwise POD parameters (Cont'd)**



6.3.2.3 Accelerator unit cost variation

As elaborated in [165], the equilibrium mass-flow balance model, for each ADS-based technology, cost optimises the cost of accelerator power through the selection of a final blanket neutron multiplication, k_{eff}^{f}, for a given initial value, k_{eff}^{i}. This final multiplication is chosen in a trade-off between accelerator power and fuel cycle operations (i.e. fuel fabrication and reprocessing) so as to minimise the cost of electricity in those ADS systems such as TRU burners that experience large reactivity swings during operation at constant power. Typical accelerator parameters required for such an optimisation are listed in Table 6.5.

The main costs for ADS-driven schemes are the additional Rest of Plant (ROP) costs arising from the power consumed by the accelerator and the capital and non-electricity O&M charges associated directly with the accelerator. In this context, the highly aggregated unit capital cost for the accelerator, UC_{beam} ($/$W_{beam}$), was judged to be the most important parameter on which to perform PSA. The accelerator efficiency was judged to offer little room for improvement, and hence was not subjected to PSA.

Table 6.5. **Typical (generic) accelerator physical and economic parameters required for the ADS accelerator "optimisation"**

Fixed physical parameters	
Target yield for E_P = 1 GeV	22.9
Neutrons per fission, ν	3
Energy yield per fission (MWth.y/kg)	2.7
Fission yield (MeV/fission)	200
Fixed system parameters	
Initial blanket multiplication, $k_{eff,i}$	0.98
Final blanket multiplication (limit), $k_{eff,f}$	0.92
Flux peaking importance function, φ_S	1
Thermal to electric conversion efficiency, ε_{th}	0.37
Accelerator efficiency, ε_A	0.45
Auxiliary (non-accelerator) power fraction, f_{Aux}	0.02
Fixed costing parameters (See Table 6.3)	
Unit cost of transmuter ($/kWe)	2 100
Unit cost of accelerator, UC_{beam} ($/$W_{beam}$)	15

Figure 6.8 illustrates the impact on the relative cost of varying UC_{beam} above and below the POD value of 15 $/$W_{beam}$. Scheme 3b is most affected by accelerator-related charges, since this scheme requires the highest number of ADSs to burn the TRU generated by a given capacity of once-through LWRs (power from an ADS would be 2-3 times as expensive as from LWRs if charges were not shared throughout the system). If the aim is to implement an ADS-transmuter under optimum economic conditions, plutonium discharged from LWRs should preferably be consumed in the less expensive systems, as is done in scheme 3c, and even more so in the double-strata scheme 4. Furthermore, ADSs should be designed to minimise the decrease in k_{eff} resulting from burn-up, and this is especially necessary in TRU burners.

Figure 6.8 also illustrates the increasing economic de-coupling of the costs of electricity from the accelerator cost in the direction of schemes 3b to 3c to 4, as both the magnitude and the gradient of the additional costs are reduced. This behaviour is shown even more clearly in Figure 6.9, which indicates a 12-20% penalty relative to the LWR once-through fuel cycle scheme even for an accelerator with zero capital costs.

Figure 6.8. **Impact of accelerator unit cost on relative cost for all fuel cycle schemes examined; only fuel cycle schemes 3b, 3c, and 4 use accelerator-based technologies**

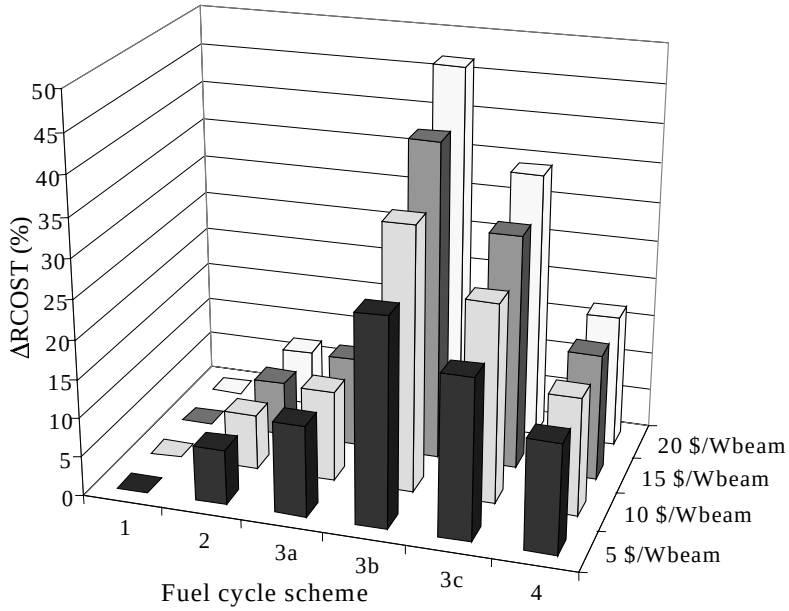
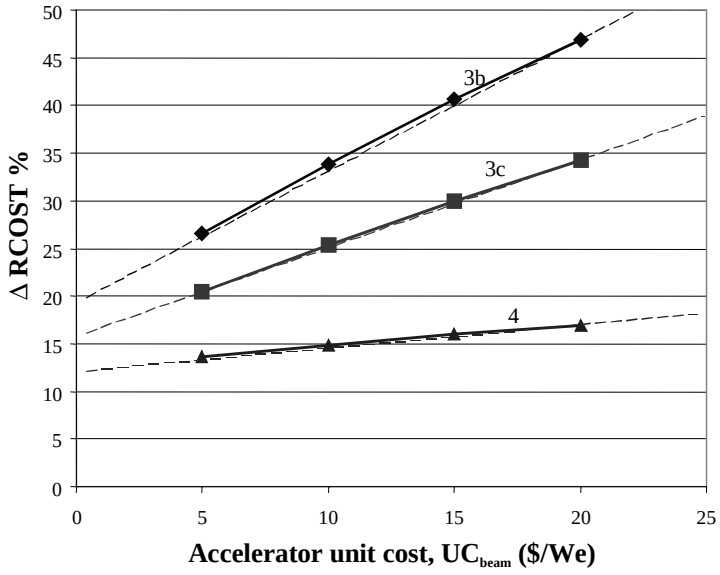


Figure 6.9**. Dependence of relative system generation cost on accelerator unit total capital cost for fuel cycle schemes based on ADS; both the magnitude and the gradient of the accelerator cost impact are reduced as less-expensive technologies are used to consume TRU**

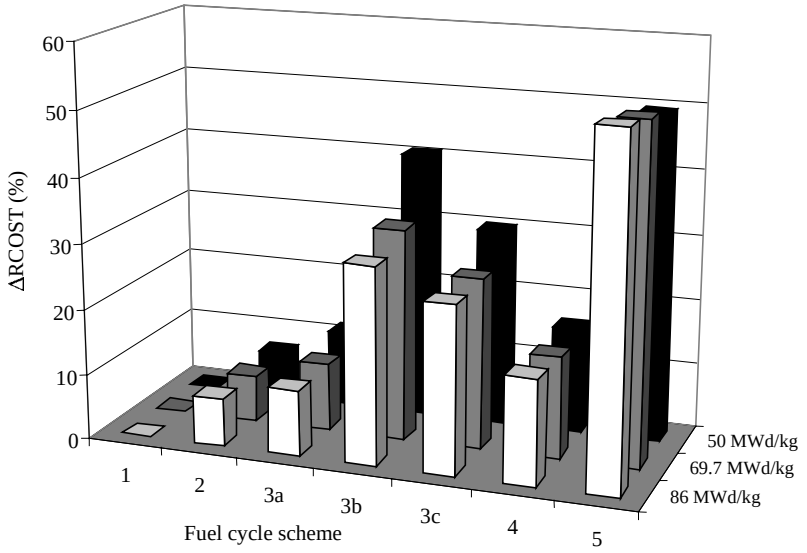


6.3.2.4 LWR burn-up variation

As was shown in the previous section, if ADS-driven transmutation technology is to be realised economically, then either the unit cost or efficiency of using accelerators must be improved, or less-expensive transmutation technologies must assume more of the burden of consuming transuranic elements. Fuel cycle schemes 3c and 4 attempt to achieve this latter goal by first fissioning as much

plutonium as is possible using more standard LWR or FR technologies. A more direct approach to reduce the burden placed on specific transmutation systems would be to achieve greater burn-up in the once-through LWRs. Preliminary results[68] indicating the impact of higher burn-up, BU (MWd/kgHM), in these driver once-through LWRs. Figure 6.10 shows the impact of increasing BU(LWR) on RCOST, and Figure 6.11 presents the shifts in the RCOST versus LOSS relations as BU(LWR) is varied. These cost impacts include the cost of higher ^{235}U enrichments required to achieve the higher burn-up values, but neither any added cost of processing more highly irradiated fuel nor the cost of added cooling storage. It is noted from Figure 6.10 that the relative cost for fuel cycle scheme 5 increases with BU in the once-through LWR technology as the normalising LWR case is becoming somewhat cheaper with increases in its BU value.

Figure 6.10. **Impact of LWR burn-up on relative overall system cost of electricity for all fuel cycle schemes considered**



6.3.2.5 Breakdown of electricity cost

Chapter 3 indicated that the different fuel cycle schemes examined need different combinations of conventional and advanced technology for reactor and fuel cycle facilities to meet the assumed steady-state equilibrium condition. Figure 6.12 shows the breakdown of the cost of electricity for the different fuel cycle schemes according the type of technology involved.[69] In general, the same structure is found as represented in Figure 2.5.

68. These results have been obtained by a different calculational methodology from the one used for the detailed mass-flow calculations in Chapter 3 and therefore need to be seen as an approximation.

69. LWR (UOX and MOX) reactor and fuel cycle facilities as well as FR-MOX reactor (Pu burner) and associated fuel cycle facilities are considered as standard technology, whereas all the rest of the technologies (FR MA/TRU burner and ADS) are considered to be advanced.

Figure 6.11. **Impact of LWR burn-up on the RCOST versus RLOSS trade-off for five of the fuel cycle schemes (the arrow shows the trend for LWR burn-up, BU, varying from 50 to 69.7 and 86 GWdth/tHM)**

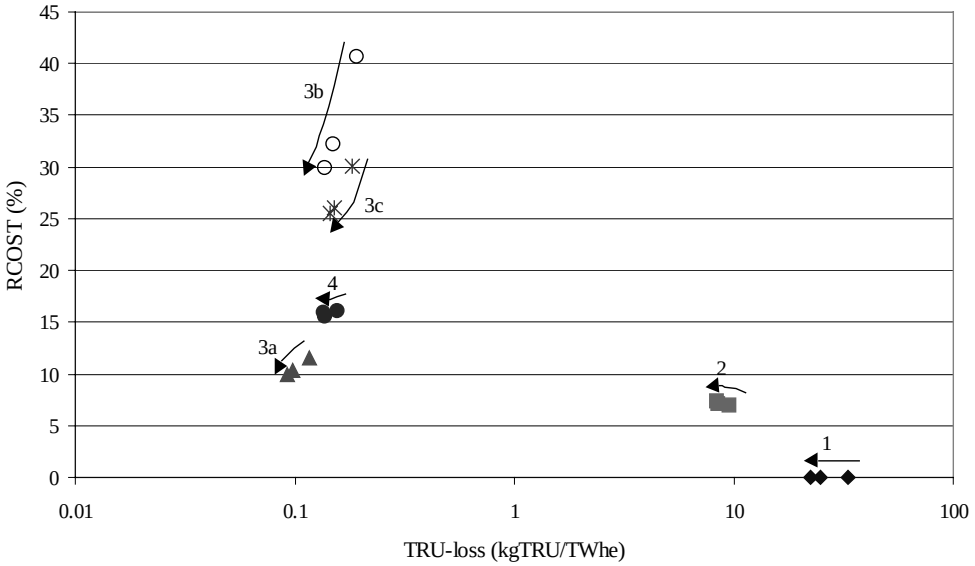
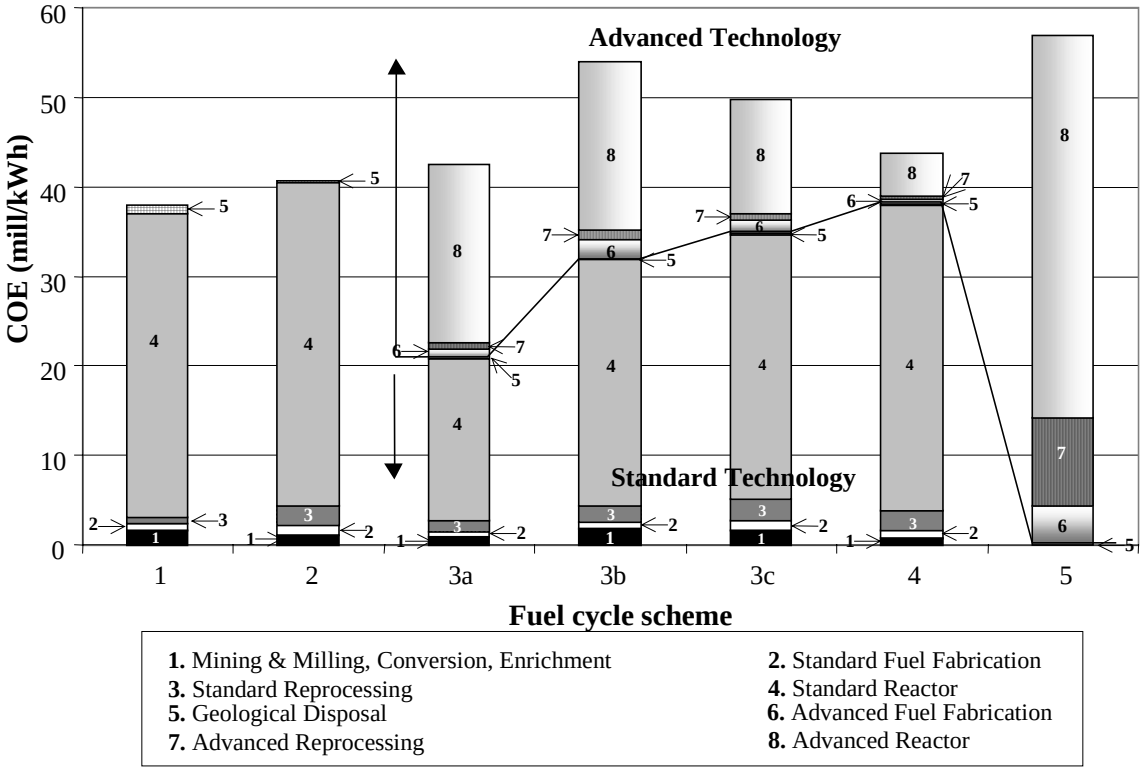


Figure 6.12. **Cost breakdown for fuel cycle schemes**



The dominant capital costs for LWR-technology, including the annual O&M charges, result in the low fraction of COE allocated to the nuclear fuel cycle in scheme 1. Chapter 3 showed that fuel cycle schemes 3c and 4 needed the least amount of advanced reactor technology in the nuclear reactor park. Figure 6.12, in combination with Figure 6.6, shows that fuel cycle schemes 3a and 4 compare rather well in terms of cost-effectiveness. The fuel cycle schemes differ significantly in financial risk, expressed as that part of the system-wide COE related to advanced fuel cycle or reactor technology, with fuel cycle scheme 4 showing both a favourable cost-effectiveness and lower financial risk. The financial risk would, however, become quite comparable if one considers the FR-MOX system to be also advanced technology. Under this assumption, the closed fuel cycles schemes 3a, 3b and 4 would involve a financial risk of about 40 to 50% of the system-wide COE. In these conditions, the fuel cycle scheme 3c would show the lowest financial risk, i.e. about 30% of COE allocated to advanced technology.

6.4 Summary conclusions

This chapter deals with the relative energy costs of the seven fuel cycle schemes examined (1, 2, 3a, 3b, 3c, 4, 5). They are expressed as cost of electricity normalised to that of scheme 1 with the once-through fuel cycle in LWRs. A relative cost of electricity was chosen to focus on the *comparative* and de-emphasise *competitive* market-oriented cost assessments. The level of this assessment is sufficient to indicate the technological improvements that might enhance the future market position of the investigated concepts, but the models used are too broadly aggregated and the extrapolation from the current technology is too large to allow a clear and meaningful rankings of the concepts for the purpose of market-base down selections to be made.

Unsurprisingly, this comparative analysis indicates that a reduction of TRU delivered to repository is accompanied by an increased *system-wide* cost of electricity. This increase is within the range 10-50%, depending on the technologies invoked. It results from increased material handling of highly radioactive fuels (e.g. in fuel fabrication and processing) and the introduction of capital-intensive transmutation technologies needed to deal with the flow of plutonium and MA from the back-end of the once-through LWR fuel cycle. Additionally, certain fuel-cycle schemes involve varying increases in the system-wide cost of electricity, depending both on the efficacy with which the advanced back-end P&T technologies deal with this material flow and the related support ratios needed to achieve the steady-state or equilibrium material balance.

In line with these observations, and in spite of the limitations of the cost-aggregated, equilibrium model used to generate these comparative results, this cost analysis allows the following conclusions to be drawn:

- Fully closed fuel cycles may be achieved with a relatively limited increase in the cost of electricity of about 10 to 20% compared to the LWR once-through fuel cycle. In the case of partially closed fuel cycles, i.e. closed only for plutonium, the cost increase is less and becomes about 7%.

- Among the fully closed fuel cycles schemes, the schemes 3a (TRU-burning in FR) and 4 (Double Strata) result into the lowest increase in system-wide cost of electricity relative to the once-through LWR normalising fuel cycle scheme 1.

- Fuel cycle schemes that involve the use of the more expensive ADS-technology show an overall economic benefit by burning as much of the plutonium as possible in less-expensive, more conventional systems, i.e. MOX-LWRs and MOX-FRs.

- The marginal cost of avoiding sending TRUs to a repository is estimated to be less than 200 000 $/kg TRU. Assuming a nominal 1% TRU content in spent fuel or high-level waste, this translates into an equivalent of less than 2 000 $/kgHM.

- For the closed fuel cycle schemes, the advanced technology contribution to the system-wide cost of electricity accounts for about 10 to 50%. If all non-LWR technology is considered as advanced, this contribution becomes about 30 to 50% except in scheme 5 where it is 100%. Fuel cycle scheme 4 benefits from burning as much as possible of the TRUs in standard technology facilities.

- The costs associated with the TRU-burning in ADS fuel cycle scheme 3b are most influenced by the accelerator-related charges, which are shared comparably between the capital charges for the accelerator and the added generation plant needed to supply it with re-circulating power. If the accelerator costs could be reduced by a factor of three, the increased cost of electricity for this fuel cycle scheme could be reduced to 25% (but still higher than for schemes 3a and 4).

- The economic incentive to increase the burn-up fraction in the TRU- or MA-burners beyond 0.15 becomes marginal. Further reductions in TRU-losses to repository at an acceptable system-wide energy costs are therefore to be obtained preferably by improvements in reprocessing technology (e.g. reduced losses and costs).

- The FBR fuel cycle scheme 5 is more expensive than the other fuel cycle schemes for the cost databases assumed. Large reprocessing charges related primarily to the blanket, needed to breed sufficient fuel for self-sustainability, represent a substantial cost item; this situation can change when more optimistic unit costs for both processing (Purex for blanket and pyro-chemical for driver fuel) and capital plant are used. On the other hand, the fuel cycle scheme 5 is not like any of the others. In addition to dealing with its actinide waste stream, it also utilises the uranium resource approximately two orders of magnitude more effectively than the other fuel cycle schemes, naturally at some cost.

Finally, this cost analysis has once again confirmed that nuclear energy may cope with its waste while limiting the extra cost that this would entail. While outside the scope of this study, it is up to society in the future to decide whether these additional costs are justified and economically acceptable in order to deliver a more sustainable nuclear energy source.