POTENTIALITIES AND COSTS OF PARTITION AND TRANSMUTATION OF LONG-LIVED RADIONUCLIDES

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Abstract

The purpose of this conceptual study is to analyse the different strategies of waste management aiming at reducing contents of long lived radionuclides by partitionning and transmutation. Different scenarios are studied; they are classified in 3 phases : the first one concerns scenarios without separation of minor actinides, the second one concerns scenarios of separation and transmutation (Np and Am) with the present technologies and the last one concerns scenarios of separation and transmutation with innovative technologies. We compare the different scenarios in term of waste material and radiotoxicity balances.The separation process is presented and we estimate a comparison between the present fuel cycle costs and the fuel cycle costs in case where we separate and transmutate Np and Am with the present technologie.

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1. OBJECTIVE AND SCOPE

The purpose of this conceptual study is to analyse the different strategies of waste management aiming at reducing contents of long lived radionuclides by partitionning and transmutation; technical ways and costs will be evaluated.

In a first step reference scenario will be defined to draw up an inventory of long lived radionuclides produce by the west European installed or foreseen reactors and estimate radiotoxicity of such nuclides.

In a second step will be estimated the expected decrease of radionuclides stockpile according to two mains scenarios : first one using presently known or available technologies, second one taking into account all foreseen innovative technologies.

After a recall of principal hypothesis, the paper presents the results concerning :

The material balance,

The potential radiotoxity (ingestion) balance,

The separation process,

An economic study.

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2. PRINCIPAL HYPOTHESIS

2.1 COMMON HYPOTHESIS FOR THE GENERAL SCENARIOS

The scenarios last for 100 years (2000 - 2100) for installed reactor park of 120 GWe, this power is at a constant level during the scenario,

The radiotoxicity is evaluated, for every cycle station, up to 10^7 years,

All the results are normalised the reference scenario (R1),

Two radiotoxicity inventories were performed :

- "waste" inventory including the radiotoxicity due to nuclear materials suitable for ultimate disposal,
- "cycle" inventory including the radiotoxicity due to nuclear materials throughout the fuel cycle (industrial facilities, interim storage, reactors and wastes).

2.2. SELECTED SCENARIOS

The study includes three main phases :

The reference scenarios without partition and transmutation of wastes :

- R1, the reference scenario with a reactor park having pressurised water reactors (PWRs) solely and burning uranium oxide (UOX), the fuel cycle is open without reprocessing.

- R2, with the same reactor park as R1, but burning UOX and MOX fuel, the cycle is closed with PUREX reprocessing (the losses are : 0.3 % for U and 0.5 % for PU) of UOX and MOX. All the plutonium is recycled in the MOX fuel. The reprocessing is made in dilution (MOX/UOX ≤ 25 %).

- R3, similar to R2 until 2020, fast reactors (FR) are progressively installed after 2020. The fabrication of the MOX fuel for the PWRs, is stopped after 2020.

To use a partition and transmutation with available technologies :

- RP1-1 is compared to the R2 scenario, it's similar until 2010. In the RP1-1 scenario, neptunium and americium are incinerated in PWRs either in homogeneous or in heterogeneous mode.

In homogeneous mode, a quantity of neptunium oxide or americium oxide representing 1 % of the total mass of heavy isotopes is mixed to the UOX fuel. The UOX + actinide fuel is reprocessed as the standard UOX fuel. The losses during reprocessing are 0.3 % for U, 0.5 % for Pu, 5 % for Np and Am and 100 % for Cm.

In heterogeneous mode, specific targets are placed in guide tubes of a UOX assembly ; the pins are made of either 100 % neptunium oxide or 30 % americium oxide with 70 % alumina. These targets are irradiated during 5 years and are not reprocessed.

- The RP1-2 scenario is compared to the R3 scenario. As the minor actinide partitioning starts in 2010, Np and Am are stored before being recycled in FRs after 2020 either in homogeneous or in heterogeneous mode.

In the homogeneous mode, an amount of Np or Am representing 2.5 % of the total mass of heavy isotopes is mixed with the FR fuel. The fuel is reprocessed as the standard FR fuel. The actinide losses during reprocessing are the same as in the RP1-1 scenario.

In the heterogeneous mode, neptunium and americium oxide targets coated with alumina are placed at the first radial breeding row of the core. These targets contain 40 % of Np or 20 % of Am of the metal mass. They are irradiated during 15 years (3 cycles) and are not reprocessed.

To use partition and transmutation with the innovative technologis after 2030.

RP2 is similar to RP1-2 until 2030 ; CAPRA type fast reactors are progressively installed after 2030 to transmutate :

- Neptunium in the homogeneous mode,
- Americium in the heterogeneous mode ; the targets are placed in the radial periphery of the core,
- Technecium and Iodine in the heterogeneous mode ; the targets are placed in the axial periphery of the core.

All the fuel and the targets are reprocessed ; the curium is separate and placed in interim storage. The losses during reprocessing are 0.1 % for U, 0.1 % for Pu, 0.5 % for Np, 0.5 % for Am, 0.5 % for Cm, 10 % for Tc and 10 % for I.

The code "COSI" (1) has been used to simulate these scenarios and to compare the material balances and the radiotoxicity.

3. RESULTS CONCERNING THE MATERIAL BALANCE

3.1. URANIUM BALANCE

• Uranium losses from reprocessing

Figure 2 shows the evolution of uranium losses from reprocessing. The values of RP1-1 respectively RP1-2, and R2, respectively R3, are comparable. The scenario RP2 permit to reduce the losses by a factor 2.5.

3.2. PLUTONIUM BALANCE

Figure 3 shows the evolution of the initial Pu content in the MOX-PWRs for scenario R2 and RP1-1. The damage of plutonium, due to plutonium recycle, results in increase the Pu content at the fabrication.

Table hereafter shows the evolution (%) of plutonium from reprocessing for scenarios R2 and RP1-1.

	SCENARIO R2 AND RP1-1				
	2020	2040	2060	2080	2100
Pu 238	4,1	6,2	7,5	8,5	8,9
Pu 239	43,8	41,9	40,4	39,2	38,7
Pu 240	26,5	26,5	26,6	26,7	26,8
Pu 241	14,7	14,1	13,4	13,0	12,9
Pu 242	10,4	10,9	11,8	12,2	12,4
Am 241	0,4	0,3	0,3	0,3	0,3

• Plutonium losses from reprocessing

Figure 4 shows the evolution of plutonium losses from reprocessing. The scenario RP2 permits to reduce the plutonium losses by a factor 4.

3.3. MINOR ACTINIDES BALANCE

Figures 5, 6 and 7 show the evolution of Np, Am and Cm mass for disposal :

- For the scenario R1, it's the mass contained in the irradiated fuels.
- The transmutation of Np permits to gain a factor 10.
- The transmutation of Am permits to gain a factor 10 in the FRS and a factor 15 in the PWRs.
- The transmutation of Am increases the production of Cm.
- For the scenario RP2, the minor actinides for disposal are principaly the mass produced before 2020 without separation.

3.4. THE MATERIAL BALANCE OF WASTES

The table shows the cumulative (tons) actinide wastes (Pu, Np, Am, Cm) in 2100.

Reprocessing wastes	R1	R2	R3	RP1-1	RP1-2	RP2
Pu	1 870	22	23	22	23	7
Np	140	100	94	12	11	7
Am	310	420	250	27	24	11
Cm	6	65	40	108	54	10

4. RESULTS CONCERNING THE RADIOTOXICITY

Figures 8 and 9 show the evolution of the potential ingestion radiotoxicity beginning in the year 2100 in the "waste" and "cycle" inventories.

The "waste" inventory takes into account :

R1 :- Losses (U) (Conversion, Fabrication) and Irradiated fuels for disposal,

R2, R3 :- Losses (U, Pu) (Conversion, Fabrication, Reprocessing) and Am, Np, Cm, F.P. (Tc 99, I 129, Cs 135) from reprocessing,

RP1-1, RP1-2 :- Losses (U, Pu, Np, Am) and Cm, FP (Tc 99, I 129, Cs 135) from reprocessing,

RP2 :- Losses (U, Pu, Np, Am, Cm, Tc 99, I 129, Cs 135).

The "cycle" inventory takes into account :

R1 :- "Wastes" inventory, Depleted Uranium and Fuel in reactors,

R2 - R3 :- "Wastes" inventory, Depleted Uranium, Uranium from reprocessing, Fuel in reactors and Interim storage (Pu, Spent fuel),

RP1-1, RP1-2 :- "Waste inventory", Depleted uranium, Uranium from reprocessing, Fuel in reactors, Interim storage (Pu, Np, Am, Spent fuel) and Targets for heterogeneous mode,

RP2 :- "Waste inventory", Depleted uranium, Uranium from reprocessing, Fuel in reactors and Interim storage (Pu, Np, Am, Cm, Tc 99, I 129, Cs 135 Spent fuel, targets).

4.1. COMMENTS ON THE "WASTE" INVENTORY

4.1.1. The reference scenarios (R2, R3)

For the short cooling times (between 10 to 1000 years) the contribution of the radiotoxicity is due to the Cm 244 (at the beginning), then to the Am 241 :

- The more important contribution of Cm 244 in the MOX fuel penalizes R2 in comparison with R1 (until 30 years).

• The Pu 241 presence in the waste for R1 ; induced a favorable balance for R2 and R3 ; the R3 balance is better because the production of Am 241 in the FR is less important than in the MOX-PWRs.

For the long cooling times (betwen 1000 to 100 000 years), the contribution is due to the Pu 239 and Pu 240. With a Pu recycle (R2 and R3) we have an important gain (5 to 10) in comparison with R1.

For the very long cooling times (between 100 000 to 5 000 000 years), the contribution is due to Np 237 and Th 229. The Pu recycle (R2, R3) reduces the Np 237 production. This reduction is more important in the fast reactor (R3).

4.1.2. The scenario using partition and transmutation with available technologies (RP1-1, RP1-2)

Significant gains (by a factor of 6) over scenario R2 and R3 are obtained for two time periods :

• between 10^2 and 10^3 years, a period when most of the radiotoxicity is attributable to Am,

• between 5.10^5 and 5.10^6 years, a period when most of the radiotoxicity is due to Np.

For the short periods, the increased Cm production appreciably limits the gains.

Transmutation of Np and Am changes little a period when most of the radiotoxicity is attributable to Pu.

Compared with scenario R1, the average gain is by a factor of 10 to 50 beyond the first 100 years.

For the heterogeneous mode who isn't showed in the figure, the comments are similar.

4.1.3. The scenario using partition and transmutation with innovative technologies after 2030 (RP2)

The separation of Cm permits to gain an important factor for the short cooling times.

The losse reduction at the reprocessing permits to reach a factor of 100 compared with scenario R1.

4.2. COMMENTS ON THE "CYCLE" INVENTORY

The results concerning the reference scenarios (R1, R2 and R3) show that the Pu recycling doesn't degrade the cycle inventory.

The contribution of "waste" inventory evoluates from case to case ; after the first 100 years, the "waste" represent :

- less than 50 % to reach 10 % after 10^7 years for the reference scenario (R2, R3),
- less than 20 % to reach 1 % after 10^7 years for the scenario RP1-1, RP1-2,
- less than 5 % to reach 0.5 % after 10^7 years for the scenario RP2.

The other important items are irradiated fuels (both in interim storages and in the reactors) ; up to 10^6 years, depleted uranium account for most of the radiotoxicity thereafter.

For the scenario R2 and RP1-1, the radiotoxicity increases during the first 100 years due to Cm production.

Transmutation of Np and Am doesn't degrade the "cycle" inventory.

5 RP1 PROCESS

5.1 PROCESS SPECIFICATIONS

The RP1 process is intended to separate U, Pu, Np, Am and the fission products. In the finished product, uranium is present as uranyl nitrate, while plutonium, neptunium and americium are found in oxide form. The process adopted must be based on existing knowledge and technology for industrial implementation by 2010.

In view of these constraints, we have designed RP1 as an extension of the PUREX process currently implemented in the UP2 and UP3 plants at La Hague. The necessity of using existing methods required us to propose some solutions that probably are penalizing in the field of process complexity and the capital and operating cost.

5.2 OPERATING PRINCIPLE

The RP1 operating principle is summarized in the flowsheet in Appendix 5.1. It is designed as an add-on to the PUREX process, with U/Pu partitioning during the first cycle.

Neptunium is retained with the uranium by redox adjustment, and U/Np partitioning occurs during the second U cycle. The Np solution is then concentrated and the Np is converted to oxide form by the same oxalate process now used for Pu. No other changes are implemented in the U and Pu lines.

Am and Cm are obtained from the refined stream of the first U/Pu cycle by coextraction with the lanthanides, followed by (Am,Cm)/lanthanide separation. Am and Cm are then separated using a selective oxidized Am extraction process; americium oxide is obtained by the oxalate process. The Cm is returned with the fission products for vitrification.

5.3 REPROCESSING PLANT DESIGN

The RP1 process is common to both PWR (UOx-MOx) and FBR reprocessing plants, with some minor differences: the head-end facilities (fuel entry, cutup and dissolution) must be adapted to the type of fuel reprocessed; the capacities of the U and Pu lines must be adapted to process requirements, and the geometry of the subcritical process equipment is different, since it depends on the fuel medium.

The plant design remains consistent with the basic RP1 options, i.e. the minor actinide separation and conversion units are situated around the periphery of a conventional PUREX plant. The actual design is based on the known concept of the UP3 plant at La Hague. Appendix 5.2 provides an overview of the integration of the new facilities in the reprocessing plant.

We have assumed that the conventional portion of the plant will not be upgraded before 2010. The technical and economic effects of implementing neptunium and americium separation will therefore not be hidden by other factors for which the economic implications are difficult to assess.

6 ECONOMIC ASSESSMENT

6.1 FINAL OBJECTIVE OF THE ECONOMIC ASSESSMENT

In addition to the technical considerations discussed in the preceding chapters, the question was also approached from an economic standpoint. The management cost of the fuel cycle R2b and R3 was compared with a management route including separation and transmutation of the minor actinides (neptunium and americium). The options assessed were those of the two Level 1 enhanced reprocessing scenarios:

- RP1-1, in which plutonium and the minor actinides (Np and Am) are incinerated in PWRs;
- RP1-2, in which the same nuclides are incinerated in FBRs.

The results are indicated relative to a reference fuel cycle management cost. The reference scenarios are the following[1]: reprocessing without separation of the minor actinides and recycling of plutonium (except for process losses) in PWRs (scenario R2) or in FBRs (scenario R3). The unit cost of each fuel cycle operation was determined for purposes of comparison.

Actinide transmutation is assumed to occur in the same types of power reactors found in the reference population, without requiring significant modifications. For the reactor portion of the fuel cycle, the RP1 scenarios therefore do not include any capital or operating cost supplement. It may be necessary to modify the fuel, however, notably the ^{235}U or plutonium enrichment, but these supplements are included in the overall fuel cycle cost.

6.2 METHOD

The fuel cycle costs were considered on an annual basis for this study, by multiplying the material flows for one year by the unit operating cost. Most of the figures are based on national or international assessments (except for reprocessing and fuel fabrication costs, which were evaluated as part of this study) and are roughly equivalent to current market prices. This approach, which does not allow for discounting, identifies the relative weight of each fuel cycle step in the scenario, but the result cannot be integrated into the cost per kWh, which is assessed using a different method.

Two or three successive steps are required:

- Step 1: determination of the capital cost of the production facilities for each fuel cycle item.
- Step 2: determination of the corresponding unit cost[2].
- Step 3: determination of the annual fuel cycle expenditure.

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[1] *The direct disposal scenario without reprocessing (R1) is used as a reference only for radiotoxicity comparisons; refer to Chapter 2 for a detailed description of these scenarios.*

[2] *This is an internationally accepted approach.*

For the reference scenarios, the unit costs for each fuel cycle item are available directly, as they have already been determined at a national (CEA[3], DIGEC[4]) or international (OECD[5]) level, and correspond approximately to market prices, although some adjustments were required to allow for special constraints (notably for Scenario R2[6]).

For the other scenarios, two items in the cycle were modified: reprocessing and actinide fuel fabrication. The method described above was applied to reprocessing to allow for process modifications. The cost of actinide fuel fabrication was estimated directly in terms of operating costs based on MOx fuel fabrication costs.

The scenarios may be compared from an economic standpoint at each step:

- Step 1: comparison of reprocessing plant capital costs (RP1-1/R2 and RP1-2/R3).
- Step 2: comparison of unit reprocessing costs.
- Step 3: comparison of fuel cycle expenditures (RP1-1/R2 and RP1-2/R3).

From a waste disposal standpoint, the scenarios were compared only in terms of the potential radiotoxicity hazard. Disposal costs for reprocessing waste were assumed constant for all the reprocessing scenarios, as the separation yields obtained by the RP1 process are not sufficient to allow decategorization of a fraction of the fuel cycle wastes. Inasmuch as the costs are compared with a reference scenario, the waste disposal cost should not have a significant effect on the results.

6.3 REPROCESSING PLANT CAPITAL COST ESTIMATE (Step 1)

6.3.1 R2 and RP1-1 Plants

This step begins with an examination of the engineering design of the R2 and RP1 processes to conceive the overall structure of the reprocessing facilities, to specify the functions they must implement and to determine their capital cost. The analysis assumes an annual plant capacity of 800 metric tons of heavy metal based on cost data for the UP3 plant at La Hague. This represents approximately half the capacity required to meet the total equilibrium reprocessing demand under scenarios R2 or RP1-1. A unit reprocessing cost estimate based on a plant of this size may be considered representative of the implications of these scenarios.

The functional structures of the R2 and RP1 plants are summarized in Appendix 5.2. As in the La Hague reprocessing plant, each function is performed in a workshop for which the capacity and functional structure were assessed. The R2 and RP1 plants implement existing techniques, and the structures (although not the capacity) of virtually all the workshops are therefore

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[3] *French Atomic Energy Commission.*

[4] *French Gas, Electricity and Coal Utility Management Board.*

[5] *Organization for Economic Cooperation and Development.*

[6] *Scenario R2, in which all the plutonium (except for process losses) is recycled as MOx fuel in PWRs, results in a Pu/(U+Pu) ratio 3.5 higher for the reprocessing plant input stream than standard UOx fuel; this implies that the corresponding adjustment of the Pu reprocessing capacity.*

comparable to those of existing facilities. The costs of the new workshops are thus extrapolated from the known figures for reprocessing plants.

The plant construction cost is then the sum of the unit costs for each workshop, together with the site and utility costs.

6.3.2 R3 and RP1-2 Plants

A different approach was used to assess the capital cost of FBR MOx fuel reprocessing plants; no industrial facilities of this type exist for which reference costs validated by experience could be itemized, as for a PWR UOx reprocessing plant.

However, in 1986 the CEA, COGEMA and SGN conducted a joint preliminary design study to estimate the capital cost of a reprocessing plant of this type with a annual capacity of 400 metric tons. The figures from that study were discounted to the economic conditions prevailing in 1992 and used as the reference for the R3 plant. The 400 $t.yr^{-1}$ capacity corresponds relatively well to the demand postulated under this scenario, in which the quantities of FBR MOx fuel to be reprocessed range from 80 to 600 metric tons per year as fast breeder reactors go online between 2030 and 2100.

The estimated cost of the RP1-2 plant is based on the assumption that the RP1 chemical process is valid for both PWR and FBR reprocessing plants, and that the differences between them are related to mechanical, thermal or criticality constraints. The differences concern mainly the head-end workshops and the first extraction workshop; the remaining facilities differ only by the magnitude of the process flows. In fact, the RP1-2 plant is an R3 plant with the addition of neptunium and americium separation and conditioning units. The flowsheet is the same as for the RP1-1 plant, and uses the same types of facilities. The cost supplement of the RP1-2 plant over the R3 plant is therefore the sum of four components:

- The neptunium line (dimensioned according to the neptunium flow).
- The fission product and lanthanide line (dimensioned according to the fission product flow, which in turn is proportional to the MWd equivalent throughput of the plant).
- The americium line (dimensioned according to the americium flow).
- The final product interim storage facilities (dimensioned according to the sum of the neptunium and americium flows).

The cost of each component may be estimated from the cost of the corresponding component in the RP1-1 plant with allowance for differences in capacity.

6.4 UNIT COST ASSESSMENT (Step 2)

6.4.1 Reprocessing

The basic principle was to assess the cost of the reprocessing operation from the capital cost of the plant, allowing for all the outlay required throughout the life of the facility and for the total cumulative production. The method was applied to the reprocessing plants included in the reference scenarios (R2 and R3) and to the Np-Am separation scenarios (RP1-1 and RP1-2).

For the lifetime of the reprocessing plant (construction, operation, decommissioning) the unit cost of the reprocessing step was determined from the following relation:

$$\text{Reprocessing cost} = \frac{\text{Discounted (capital + renovation + decommisioning + operating costs)}}{\text{Discounted (total production)}}$$

The capital, renovation, decommissioning and operating costs were determined from the construction cost with the following hypotheses:

- Capital cost = construction cost + interim interest

  The plant construction was assumed to last 10 years; the annual capital cost breakdown was based on observed figures for typical nuclear facilities; the expenditures were discounted to the date of commercial startup.

- Renovation

  ¥ First renovation beginning the 11th year of operation, representing 30% of construction cost, amortized over 15 years and discounted to the date of commercial startup.

  ¥ Second renovation beginning the 26th year of operation, representing 5% of construction cost, amortized over 5 years and discounted to the date of commercial startup.

- Final shutdown after 35 years of operation

- Decommissioning over a 5-year period after final shutdown, representing 35% of construction cost, discounted to the date of commercial startup.

- Annual operating cost representing 5% of construction cost, discounted to the date of commercial startup; a 1% annual increase in the operating cost was assumed.

  The discounting rate (5% for this study) naturally affects the absolute value of the result, but has no effect on the relative value.

Estimated Cost

The reprocessing cost is directly proportional to the construction cost:

$$\text{Reprocessing cost} = (\text{Construction cost}) \times K$$

The unit cost supplements for RP1-1 relative to R2, and for RP1-2 relative to R3, are therefore the same as those determined for the construction costs:

Relative Cost Supplement of Enhanced Reprocessing	
$\frac{(RP1.1 - R2)}{R2} = 0.35$	$\frac{RP1.2 - R3}{R3} = 0.48$

6.4.2 Actinide Fuel Fabrication

A different approach was used to assess the actinide fuel fabrication step. It was assumed that the fabrication process itself will not raise insurmountable difficulties, and attention therefore focused on the radiation protection requirements imposed by the addition of neptunium and americium to existing fuel fabrication processes.

Homogeneous recycling of neptunium with UOx fuel in a mixed oxide fuel fabrication facility such as MELOX appears to be a viable solution, subject to enhancement of biological shielding, notably during the initial process steps.

The feasibility of fabricating a homogeneous fuel containing 1-2% americium in the same type of facility remains to be demonstrated. In any event, the entry of AmO_2 powder into the facility would require a very high degree of automation. Even after blending, americium recycling would increase the specific activity of the process stream by a factor of 10 compared with actual MOx fuel fabrication. Under these conditions, the maximum specific activity level specified for the initial container discharging station in MELOX would prevail throughout the fuel fabrication cycle.

A detailed assessment of the cost of these modifications is beyond the scope of this investigation.

The use of MELOX or similar technology for the fabrication of fuel containing neptunium or americium would require a number of modifications (additional shielding, automation) to avoid higher occupational doses; these modifications could result in a fabrication cost supplement of 20% over MOx fuel fabrication. **This value will be used as the reference for the remainder of this investigation**, although two additional values (+ 10% and + 100%) were considered in a sensitivity study. The first reflects the fact that the fabrication of UO_2 + NpO_2 + AmO_2 fuel will cost at least as much as MOx fuel, and that even under ideal circumstances, some modifications would be necessary, resulting in a minimum cost supplement of 10%. The second figure assumes that the glove box technology implemented in the MELOX plant must be abandoned, and that a different shielded line technology must be developed, with a major impact on fabrication costs. A figure of + 100% must not be taken too literally, as it was not obtained by a serious evaluation but is only postulated to assess the sensitivity of the overall results to a significant increase in the actinide fuel fabrication cost.

The relative cost supplement over the reference scenario, which could be the cost of either UOx or MOx fuel fabrication, is indicated below:

Relative Unit Cost Supplement of Actinide Fuel Fabrication Compared with:	
UOx fuel	2.6 < **2.9** < 5.5
MOx fuel[7]	0.1 < **0.2** < 1.0

6.5 COMPARATIVE FUEL CYCLE COSTS (Step 3)

The expenditures are calculated year after year by multiplying each item in the fuel cycle material or service balance by the unit cost. All the calculations are performed in constant French Francs under the economic conditions prevailing in 1992, without discounting.

Tow material and services balance was done :

- A cumulative balance throughout the duration of each scenario, reflects the relative importance of each scenario because it integrates all the transient phases.

[7] *The cost of MOx fuel fabrication is roughly 3.25 times that of UOx fuel.*

- A typical steady state annual balance, minimizes the inertia factor in the fuel cycle especially for the FBR scenarios that change for the duration of the study.

The comparison of fuel cycle expenditure, were made from three types of balances without any discounted cost :

* Yearly balances, showing the evolution of cycle expenditures year by year.

* Cumulated balances over the duration of the scenarios, which take into account the effects of inertia of the scenarios.

* Current year balances, taken at the end of the period to be as close as possible to stable state. This type of comparison is significant of the differences of nature between scenarios. It is the only one we will discuss about here after.

At the end we carry out a sensitivity study, in order to assess the impact of a variation of the unit operating costs on the global results.

6.5.1 Typical Steady-State Annual Balance

6.5.1.1 R2 and RP1-1 scenarios

This assessment concerns a typical year of steady-state operation after 2040. The graph in Appendix 6.1 indicates the absolute outlay assigned to each cycle item for scenarios R2 and RP1-1.

The expenditures for scenario RP1-1 systematically exceeded those of scenario R2. At the front end of the cycle, this is due to the larger material balance and to the fabrication of UOx fuel containing actinides; for the back end, it is attributable to higher reprocessing costs.

Reprocessing (15%) and actinide fuel fabrication (17%) are the most significant additional expenditures incurred by transmutation of the minor actinides. Uranium mining and enrichment each represent 2.5% cost supplements, while the UOx fuel fabrication item diminishes by about 4% (again, it must be noted that the value of uranium and plutonium was deliberately considered nil, and not as material assets).

Under steady-state conditions, the total fuel cycle outlay under scenario RP1-1 exceeds that of R2 by 33%. Appendix 6.2 details the relative weight of each item in the overall steady-state annual balance for both scenarios.

Reprocessing is the dominant item in both scenarios; scenario RP1-1 also includes actinide UOx fuel fabrication. The following remarks may be made concerning these points:

- The importance of reprocessing (45%) is not surprising, and is consistent with the annual expenditure approach adopted for this study. This result cannot be directly compared with previously published economic assessments in which reprocessing represents only about 30% of the conventional fuel cycle cost: such figures clearly show the effect of discounting, which minimizes the value of outlay in the distant future compared with immediate outlay. No such effect is observed in this investigation, as the costs were not discounted. The

reprocessing cost is also increased over that of conventional reprocessing[8] because of massive plutonium recycling (R2) and the implementation of enhanced reprocessing methods (RP1-1).

- Recycling of minor actinides in UOx fuel is certainly not the best solution from a purely economic standpoint, as it subjects a large fraction of the UOx flow to fabrication costs comparable to those of MOx fuel, representing a three-fold cost supplement. If it were technically feasible, it would be preferable to recycle the largest possible actinide fraction in MOx fuel, the fabrication of which is already penalized by radiation protection constraints, and for which a few additional percent of neptunium or americium should have a lower impact on the fabrication costs.

6.5.1.2 R3 and RP1-2 Scenarios

These scenarios involve both PWR and FBR plants, and the assessment is therefore compiled using cycle costs estimated from different types of sources:

- Data based on current industrial experience for PWR cycle costs.
- Research data that have not been qualified industrially for FBR cycle costs.

Because of the different reliability of these estimates, errors may ensue that cannot be estimated at the present time; the following results must therefore be interpreted cautiously.

This assessment concerns the year 2090. The graph in Appendix 6.3 indicates the absolute outlay assigned to each cycle item for scenarios R3 and RP1-2.

The expenditures for scenario RP1-2 systematically exceed those of scenario R3. The higher front-end cycle costs of scenario RP1-2 are due mainly to increased outlay for actinide MOx fuel fabrication (2%). This supplement is minimal compared with the back-end cost supplements for PWR reprocessing (12%) and FBR reprocessing (14%). FBR fuel reprocessing is considerably more penalizing that in the cumulative balance because at the end of the scenario the FBR cycle expenditure is not weighted by integration of the balances over the entire duration of the scenario. In 2090, the proportion attributable to FBR reprocessing continues to rise as PWR reprocessing expenditure declines.

In a typical operating year, the total outlay for scenario RP1-2 exceeds that of scenario R3 by 28%. The graph in Appendix 6.4 indicates the relative weights of each item in the overall cycle outlay during a typical year. Reprocessing is the principal item in both scenarios, accounting for about 60% of the total.

6.5.2 Sensitivity of Estimates to Unit Cost Hypotheses

The results of the economic assessment depend directly on the unit operating costs. The figures used for this study were obtained from a variety of sources and are not all equally reliable. Three data categories were considered:

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[8] *Reprocessing of standard UOx fuel (33 GWd.t^{-1}) with a Pu/(U+Pu) ratio of about 1%, with separation of U, Pu and fission products.*

[9] *In this case, the increased productivity of industrial operation was factored into the final figure.*

- The costs of operations now performed in the fuel cycle have been validated by industrial or semi-industrial[9] experience. For the purposes of this sensitivity study, these costs are considered to be known without any uncertainty margin. They include uranium mining, conversion and enrichment, PWR (UOx and MOx) fuel fabrication, FBR MOx (fertile and fissionable) fuel fabrication, spent fuel transportation and R'2 reprocessing. This category also includes waste transportation and disposal, which affect both the conventional cycle scenarios and the partitioning/transmutation scenarios in the same hypothetical manner.

- The cost of operations estimated from design studies but unconfirmed by industrial implementation are assigned an uncertainty margin.

- The cost of operations that have not been analyzed in detailed design studies are considered to have a very large uncertainty margin. These mainly include PWR UOx and FBR MOx actinide fuel fabrication costs.

To evaluate the effect of possible unit cost variations on the final result of the economic assessment, the results were recalculated to take into account the upper limit of the uncertainty margin (high estimate) and the lower limit of the uncertainty margin (low estimate) on the unit costs specific to partitioning and transmutation operations. All the other costs remained constant at their reference values. The results are indicated in the table below. Under the assumptions of this study, compared with the conventional fuel cycle scenarios, the partitioning/transmutation scenarios imply a cycle cost supplement ranging from 20% to 55% for the PWR scenario, and from 10% to 50% for the FBR scenario.

Basis	$\frac{RP1.1 - R2}{R2}$		$\frac{RP1.2 - R3}{R3}$	
	Typical Year	**Cumulative**	**Typical Year**	**Cumulative**
High Estimate	54%	44%	52%	29%
Reference	**33%**	**27%**	**28%**	**17%**
Low Estimate	21%	17%	11%	7%

7 CONCLUSION

The study of different transmutation (Np and Am) scenarios have permit to show that it's possible to gain an important factor on the waste radiotoxicity generated by a reactor park and cycle plants. Compare with scenario R1 (open cycle), the gain is by a factor 40 to 100 beyond the first 100 years and according the cooling time. The gain is better when we use the fast reactors to transmute Np and Am. If we want to increase the gain, the separation of Np, Am and Cm must begin as soon as possible because in the future, the past will have an important weight for the evolution of the waste radiotoxicity. Transmutation of Am and Cm doesn't degrade the "cycle" inventory.

The average fuel cycle cost supplement resulting from the implementation of partitioning and transmutation of Pu, Np and Am (scenarios RP1-1 and RP1-2) above the cost of the reference scenarios (R2 and R3) in which only plutonium is recycled, should be approximately from 20% to 55% for the PWR scenario and 10% to 50% for the FR scenario.

The average cost supplements are slightly higher for a fuel cycle based on transmutation of the minor actinides in PWRs than for a cycle using fast reactors; however, the uncertainty margins on unit operating costs are such that this difference is probably not significant.

These results are based on relatively unfavorable hypotheses (implementation of complex processes, recycling of minor actinides in UOx fuel, reprocessing plant design). It is not unreasonable to expect that ongoing research and development work - notably in France under the SPIN program - will allow simpler processes to be designed in the future to achieve the same objectives.

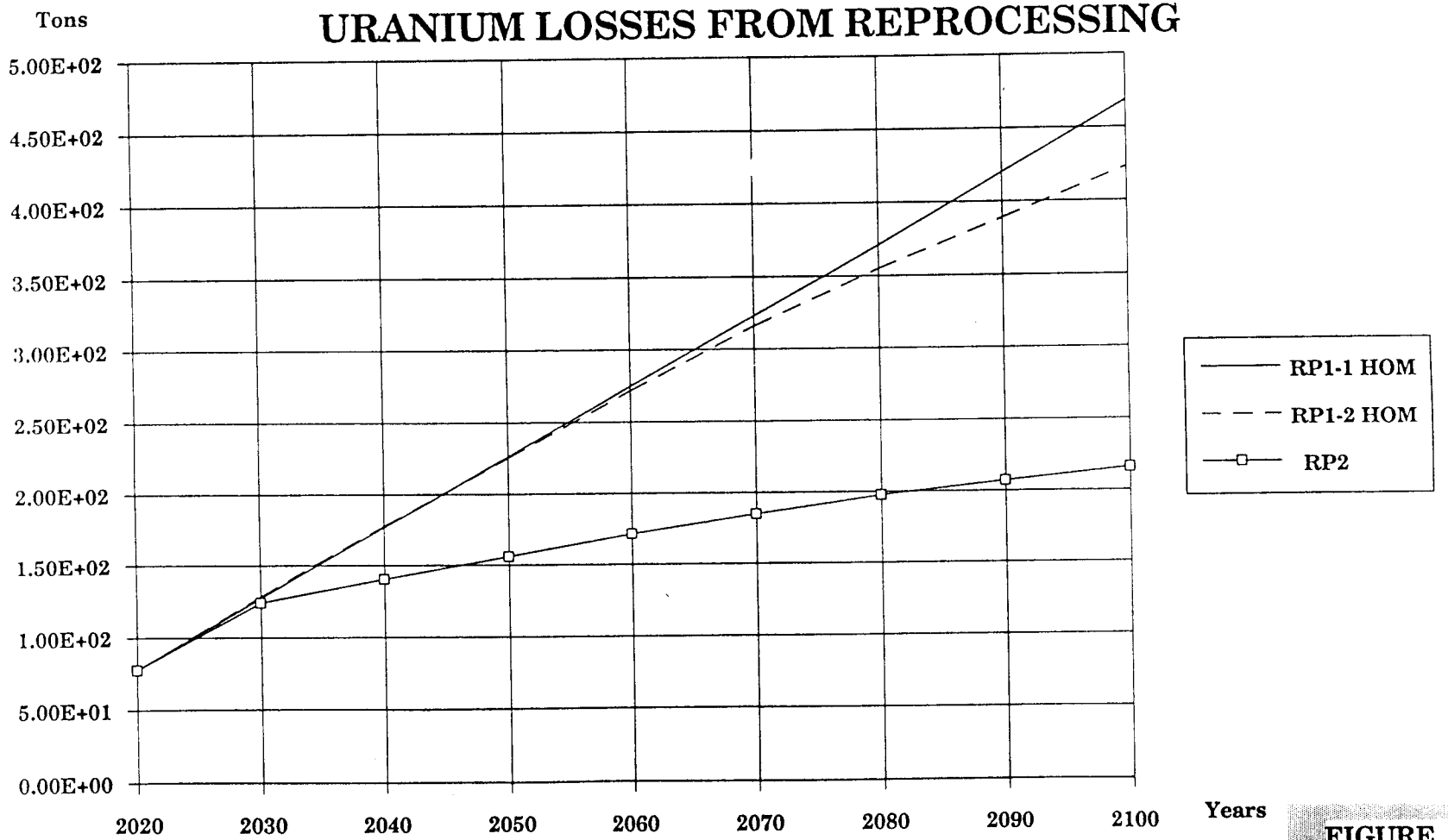

URANIUM LOSSES FROM REPROCESSING
Tons
5.00E+02
4.50E+02
4.00E+02
3.50E+02
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years
RP1-1 HOM
RP1-2 HOM
RP2

FIGURE 2

SCENARIO R2 : INITIAL PU CONTENT IN THE MOX-PWRS

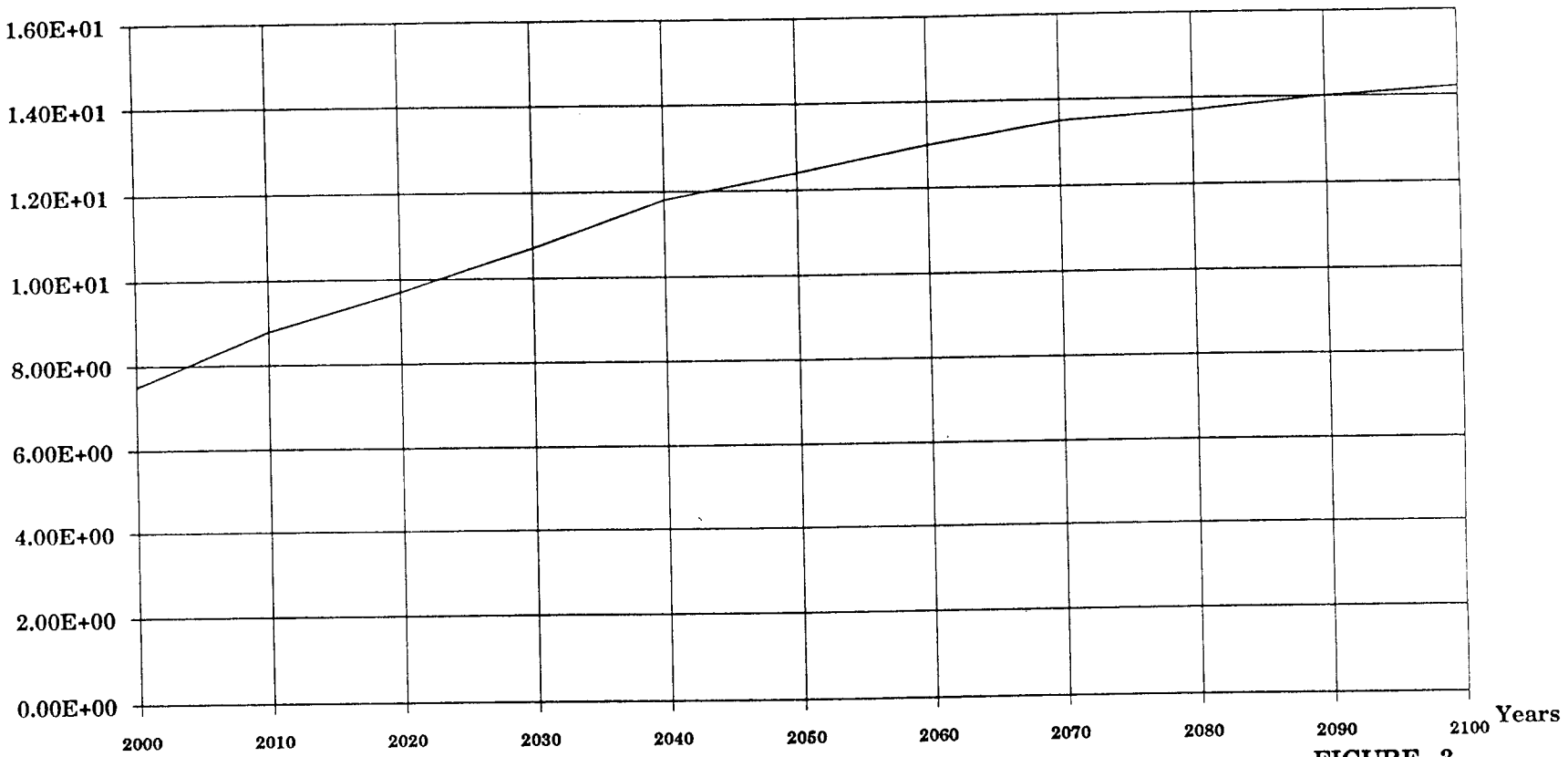


FIGURE 3

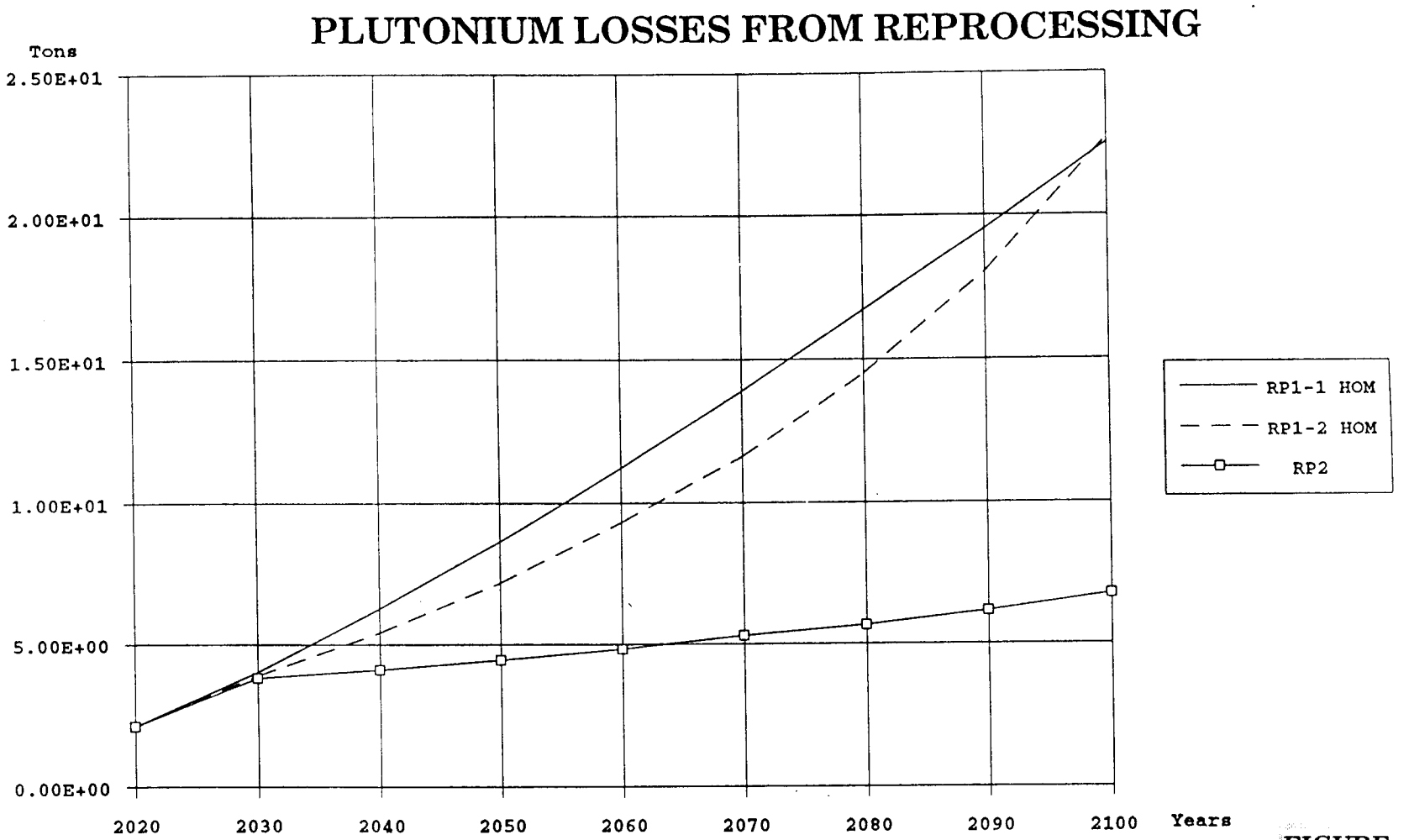

PLUTONIUM LOSSES FROM REPROCESSING
Tons
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years
RP1-1 HOM
RP1-2 HOM
RP2

FIGURE 4

NEPTUNIUM FOR DISPOSAL

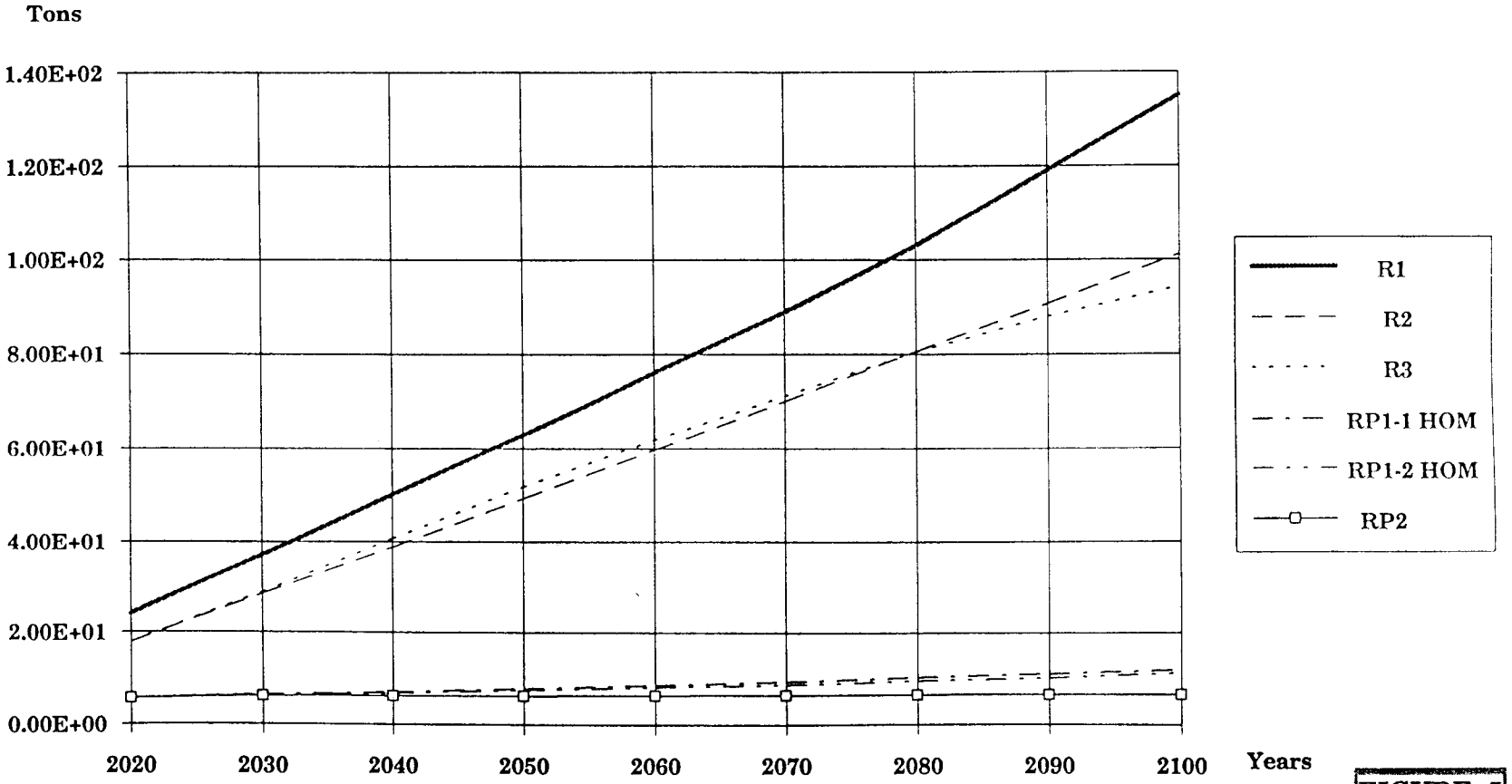


FIGURE 5

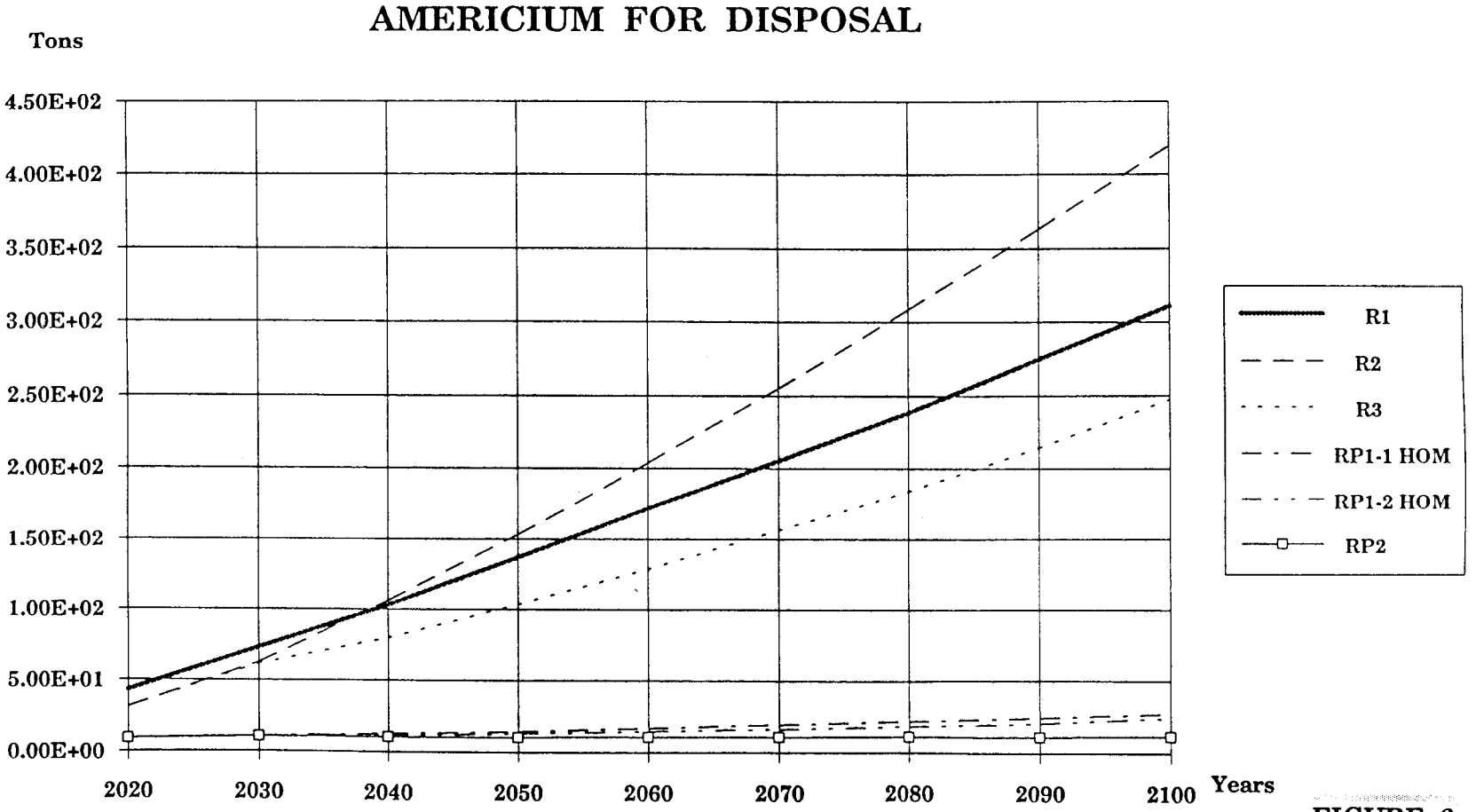

AMERICIUM FOR DISPOSAL
Tons
4.50E+02
4.00E+02
3.50E+02
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years
R1
R2
R3
RP1-1 HOM
RP1-2 HOM
RP2

FIGURE 6

CURIUM FOR DISPOSAL

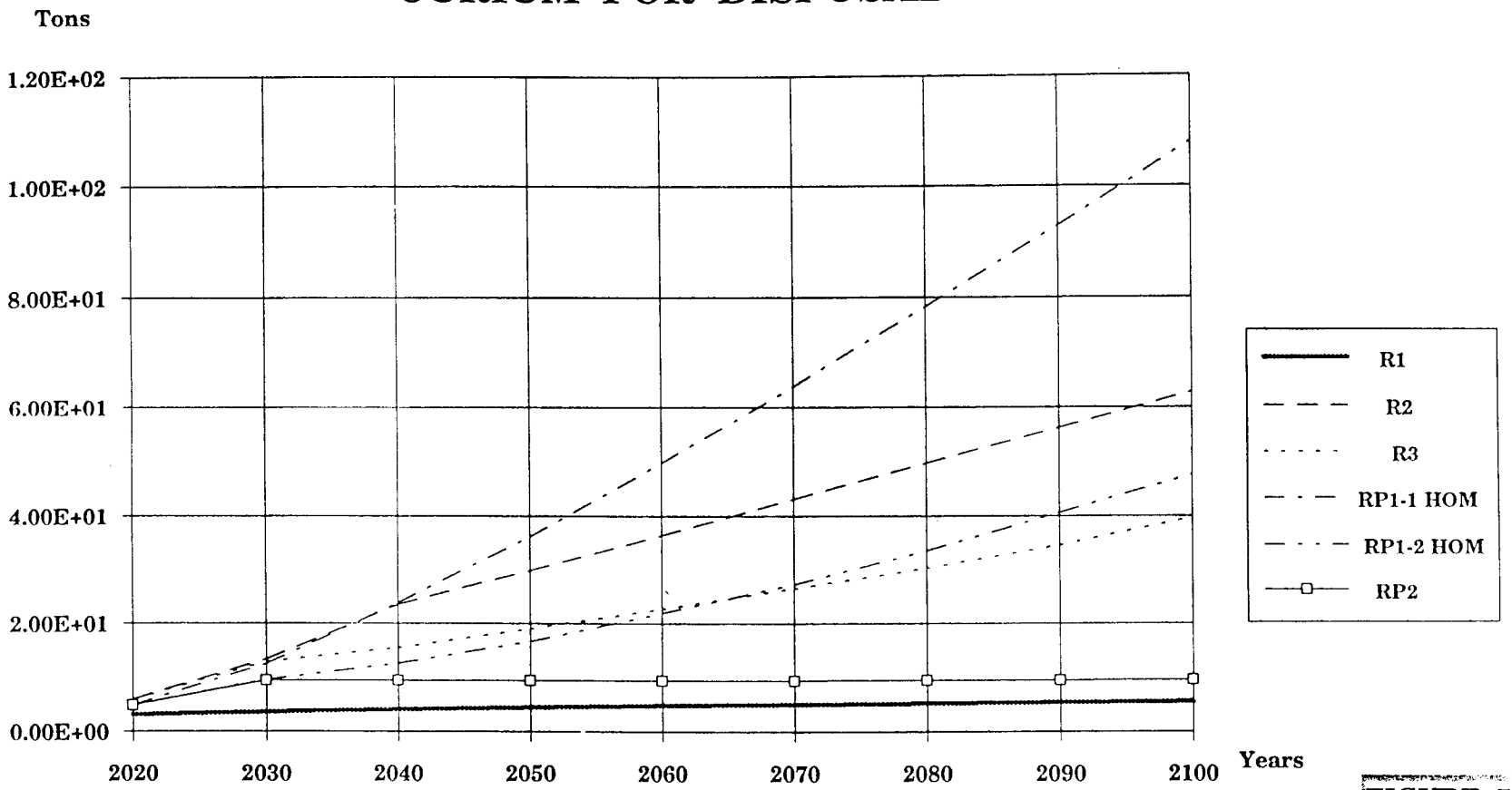


FIGURE 7

POTENTIAL INGESTION RADIOTOXICITY : "WASTE" INVENTORY

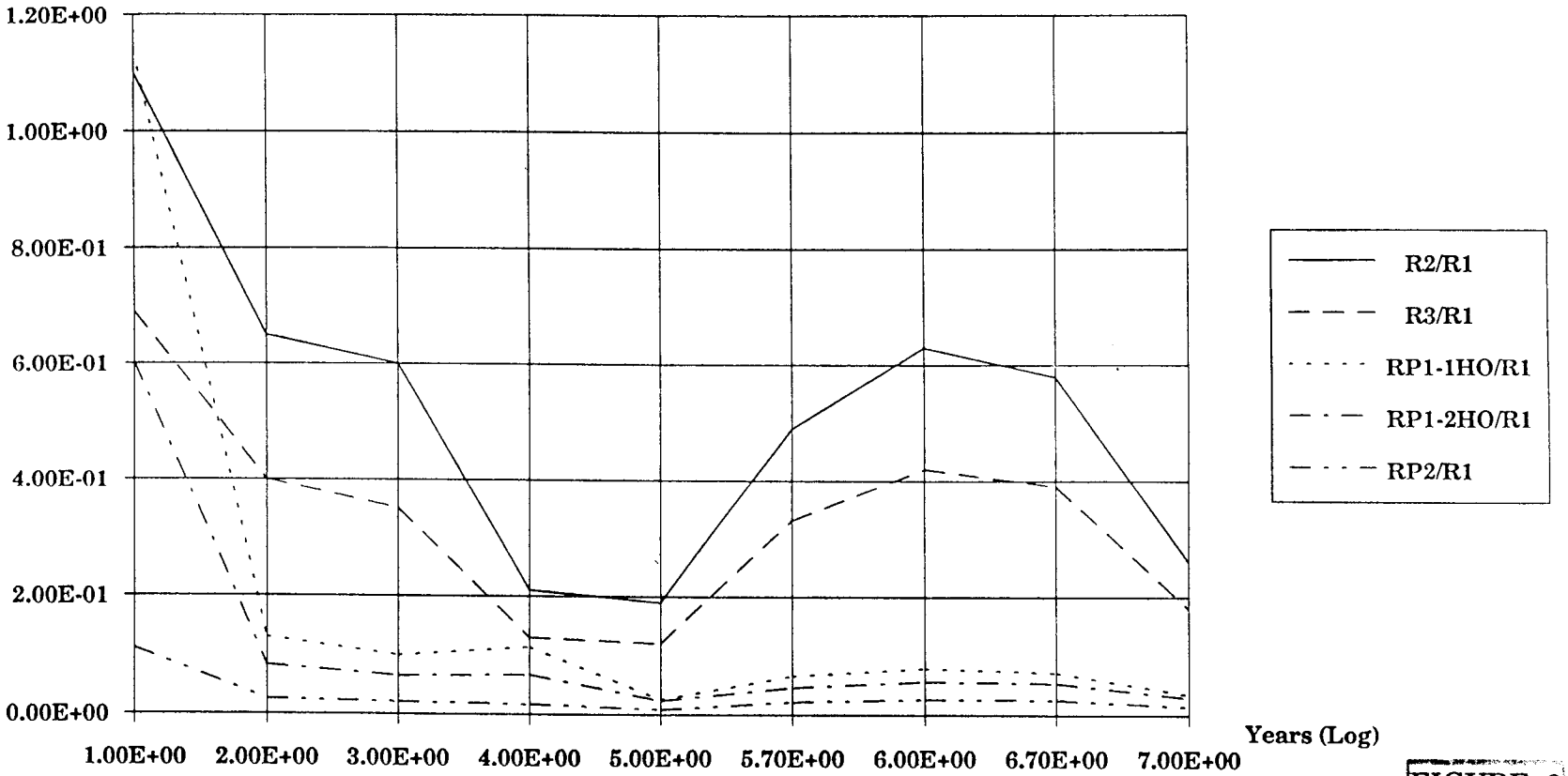


FIGURE 8

POTENTIAL INGESTION RADIOTOXICITY : "CYCLE" INVENTORY

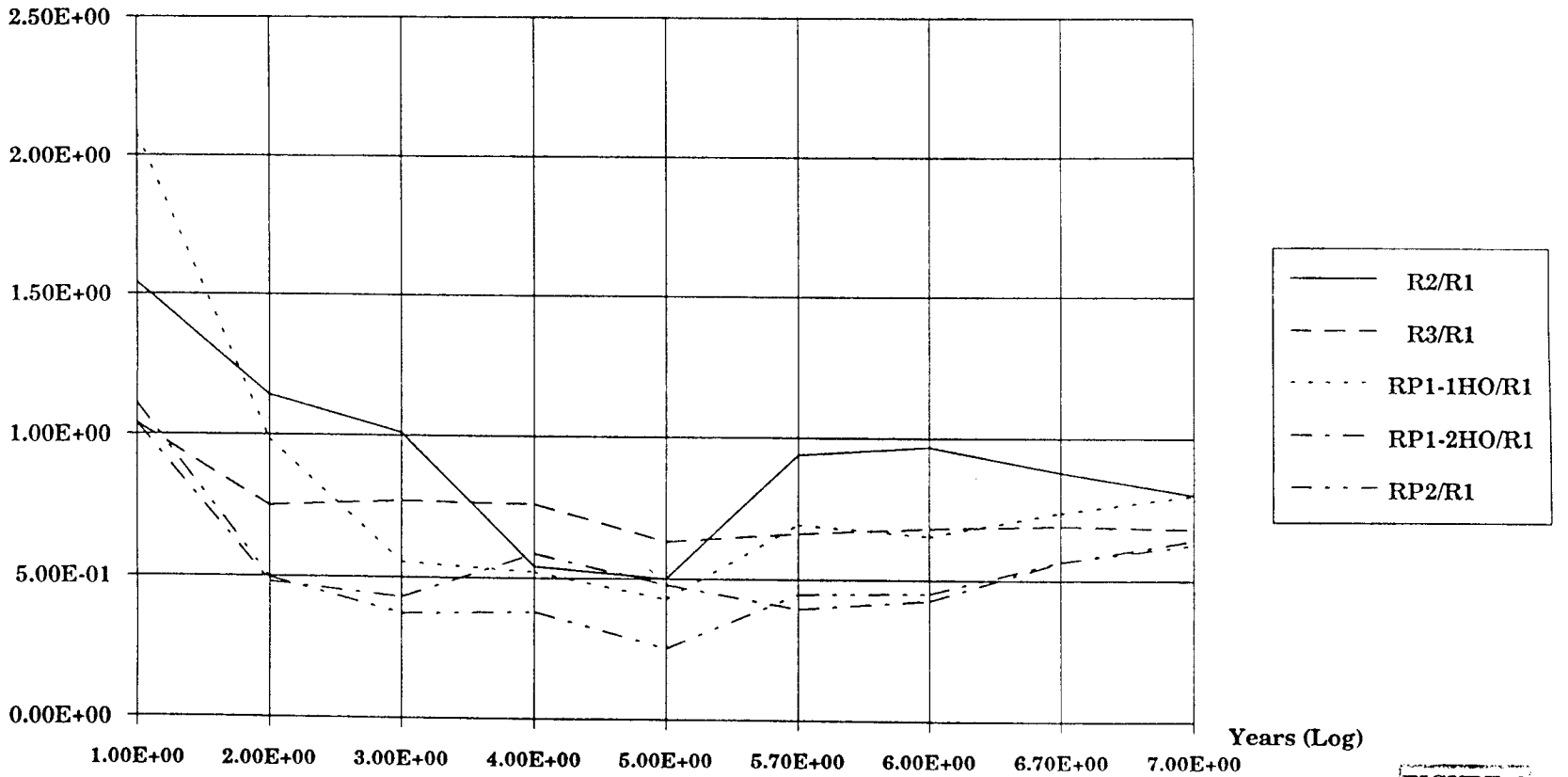


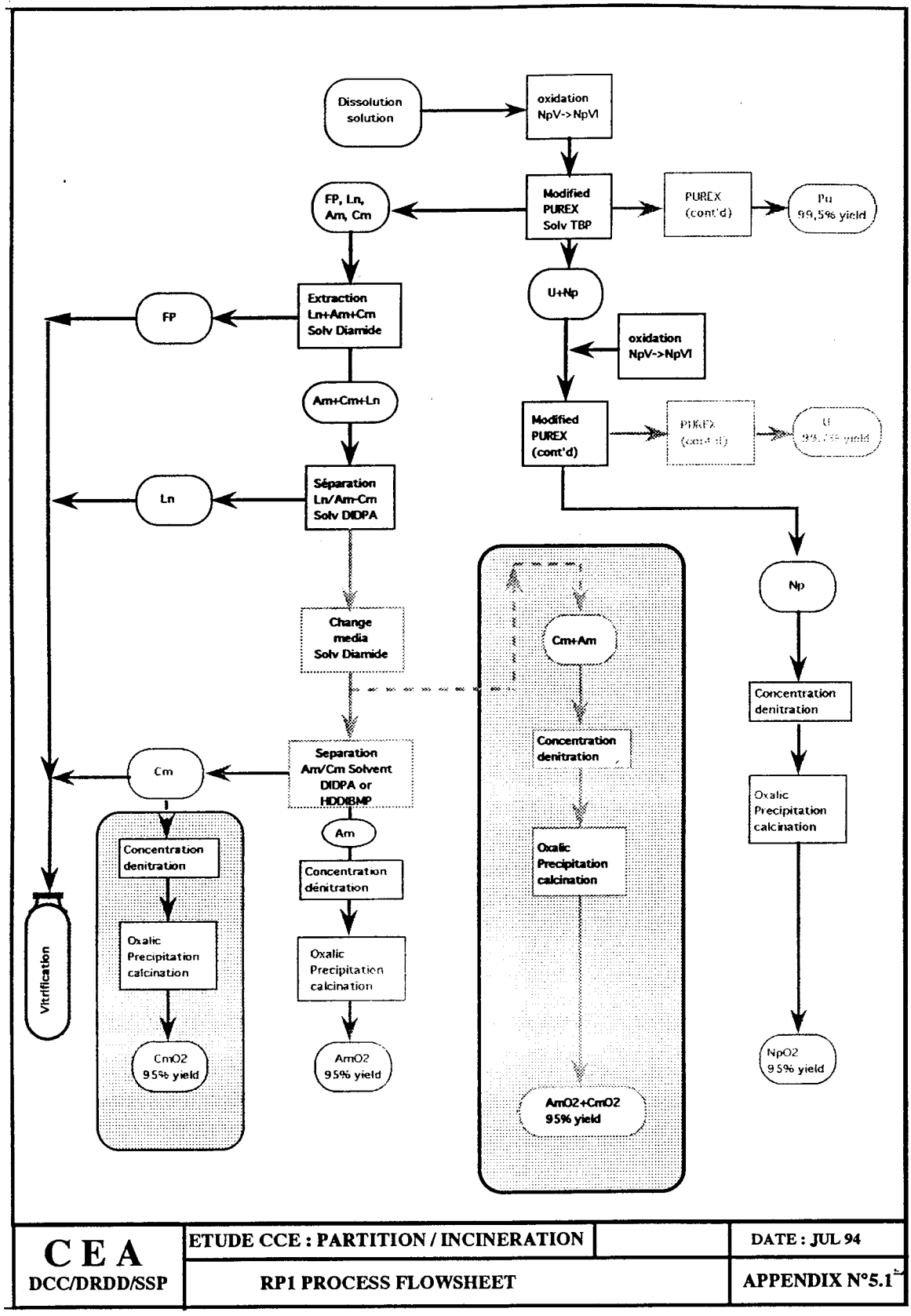
FIGURE 9

Référence :

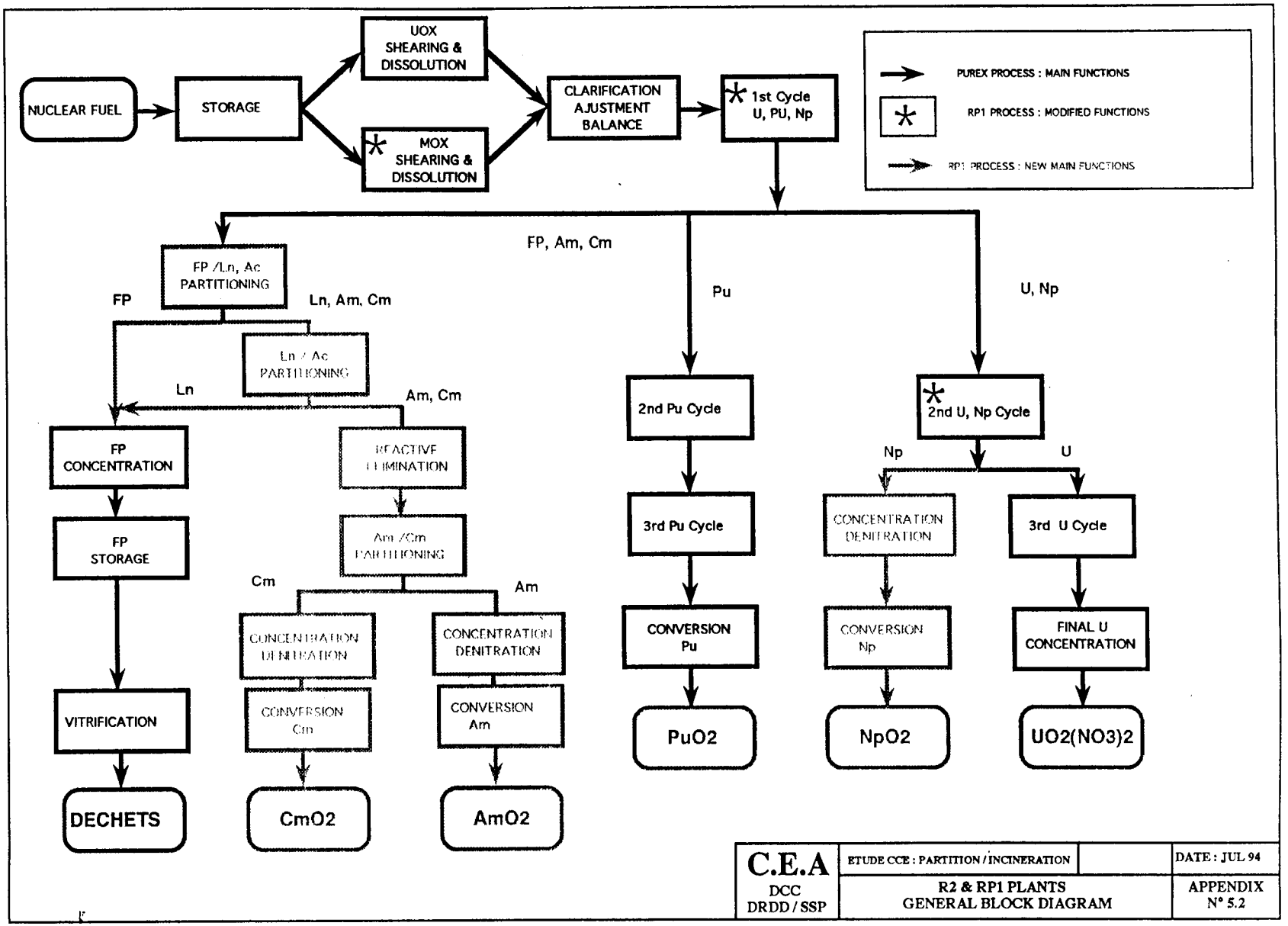
(1) COSI, a simulation software for a pool of reactors and fuel cycle plants - Application to the study of the deployment of F.B.R.

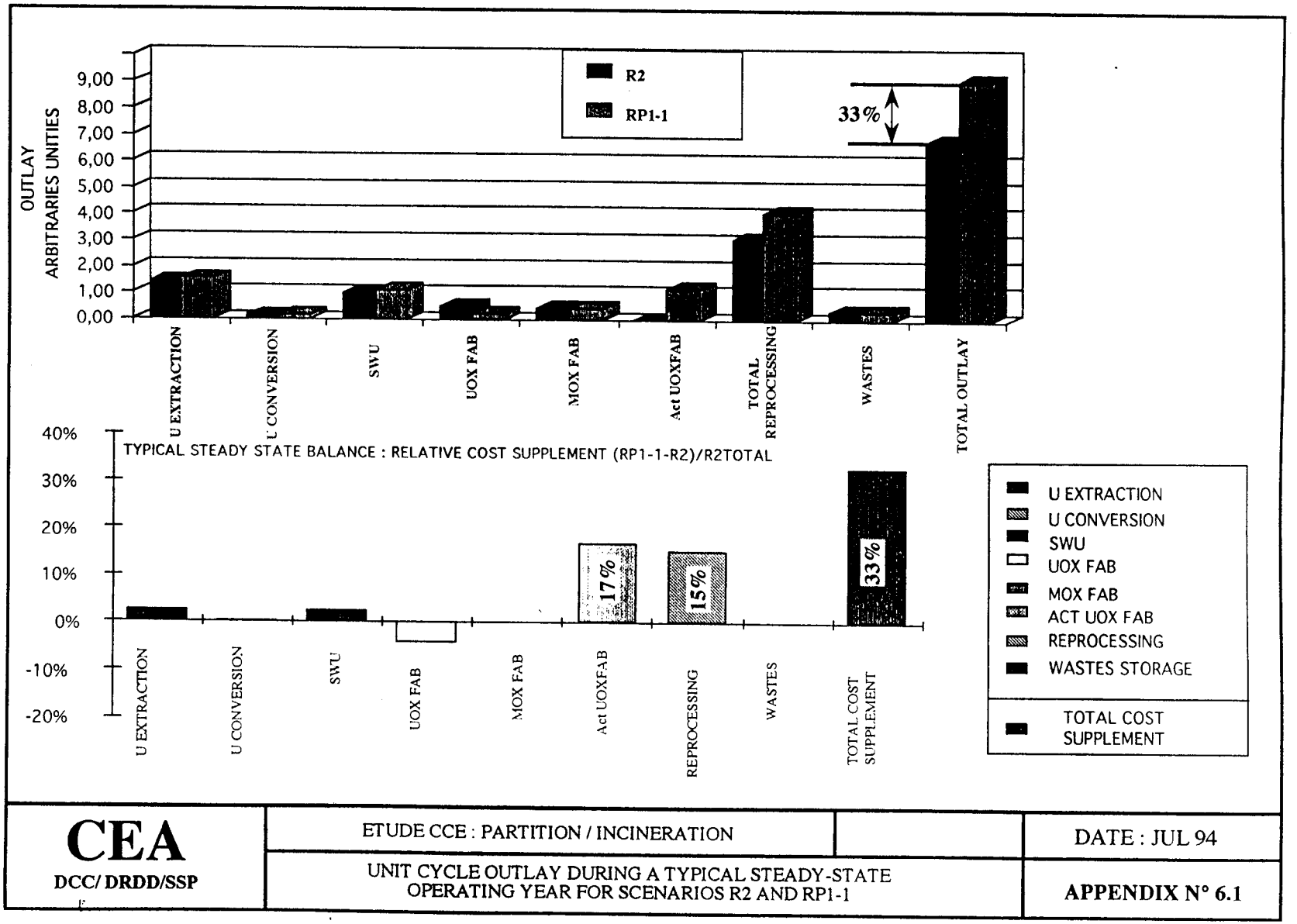
Log n° PA 185 KYOTO, Japan 1991

List of Appendices

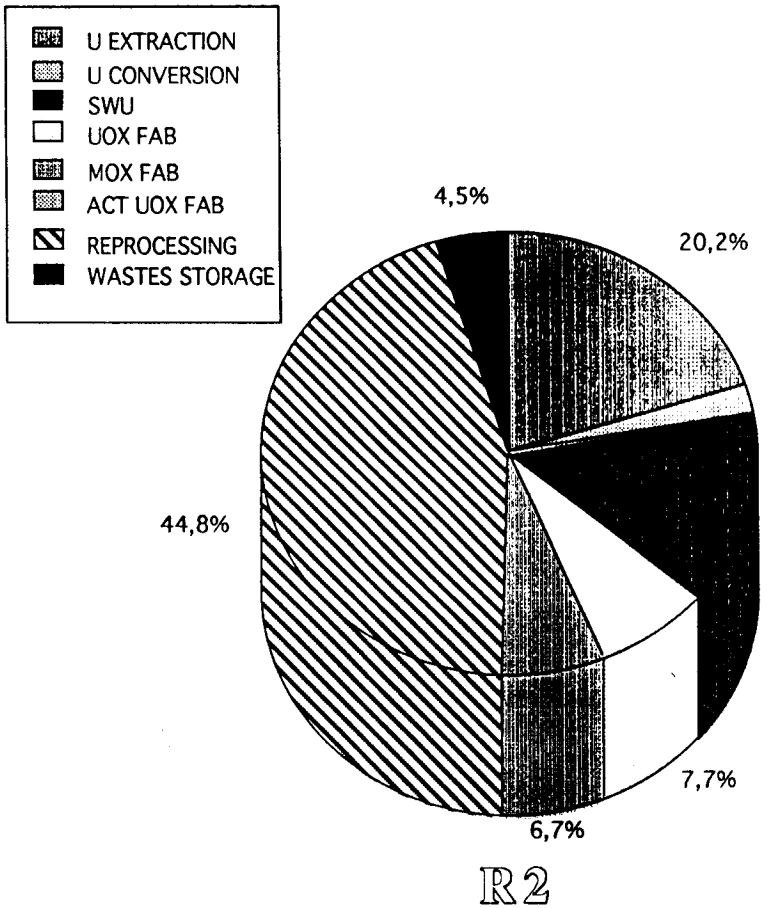


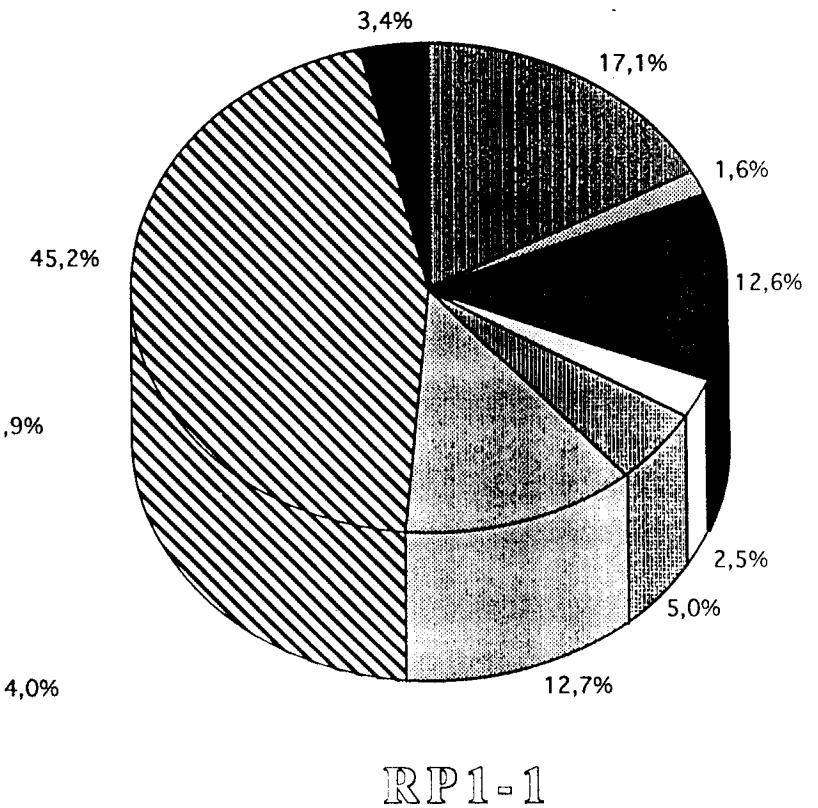
CEA DCC/DRDD/SSP	ETUDE CCE : PARTITION / INCINERATION	DATE : JUL 94
	RP1 PROCESS FLOWSHEET	APPENDIX N°5.1


NUCLEAR FUEL
STORAGE
UOX SHEARING & DISSOLUTION
MOX SHEARING & DISSOLUTION
CLARIFICATION AJUSTMENT BALANCE
1st Cycle U, PU, Np
PUREX PROCESS : MAIN FUNCTIONS
RP1 PROCESS : MODIFIED FUNCTIONS
RP1 PROCESS : NEW MAIN FUNCTIONS
FP, Am, Cm
Pu
U, Np
FP /Ln, Ac PARTITIONING
FP
Ln, Am, Cm
Ln / Ac PARTITIONING
Ln
Am, Cm
FP CONCENTRATION
FP STORAGE
VITRIFICATION
DECHETS
REACTIVE ELIMINATION
Am /Cm PARTITIONING
Cm
Am
CONCENTRATION DENITRATION
CONVERSION Cm
CONCENTRATION DENITRATION
CONVERSION Am
CmO2
AmO2
2nd Pu Cycle
3rd Pu Cycle
CONVERSION Pu
PuO2
2nd U, Np Cycle
Np
U
CONCENTRATION DENITRATION
CONVERSION Np
NpO2
3rd U Cycle
FINAL U CONCENTRATION
UO2(NO3)2
C.E.A
DCC
DRDD / SSP
ETUDE CCE : PARTITION / INCINERATION
DATE : JUL 94
R2 & RP1 PLANTS
GENERAL BLOCK DIAGRAM
APPENDIX
N° 5.2

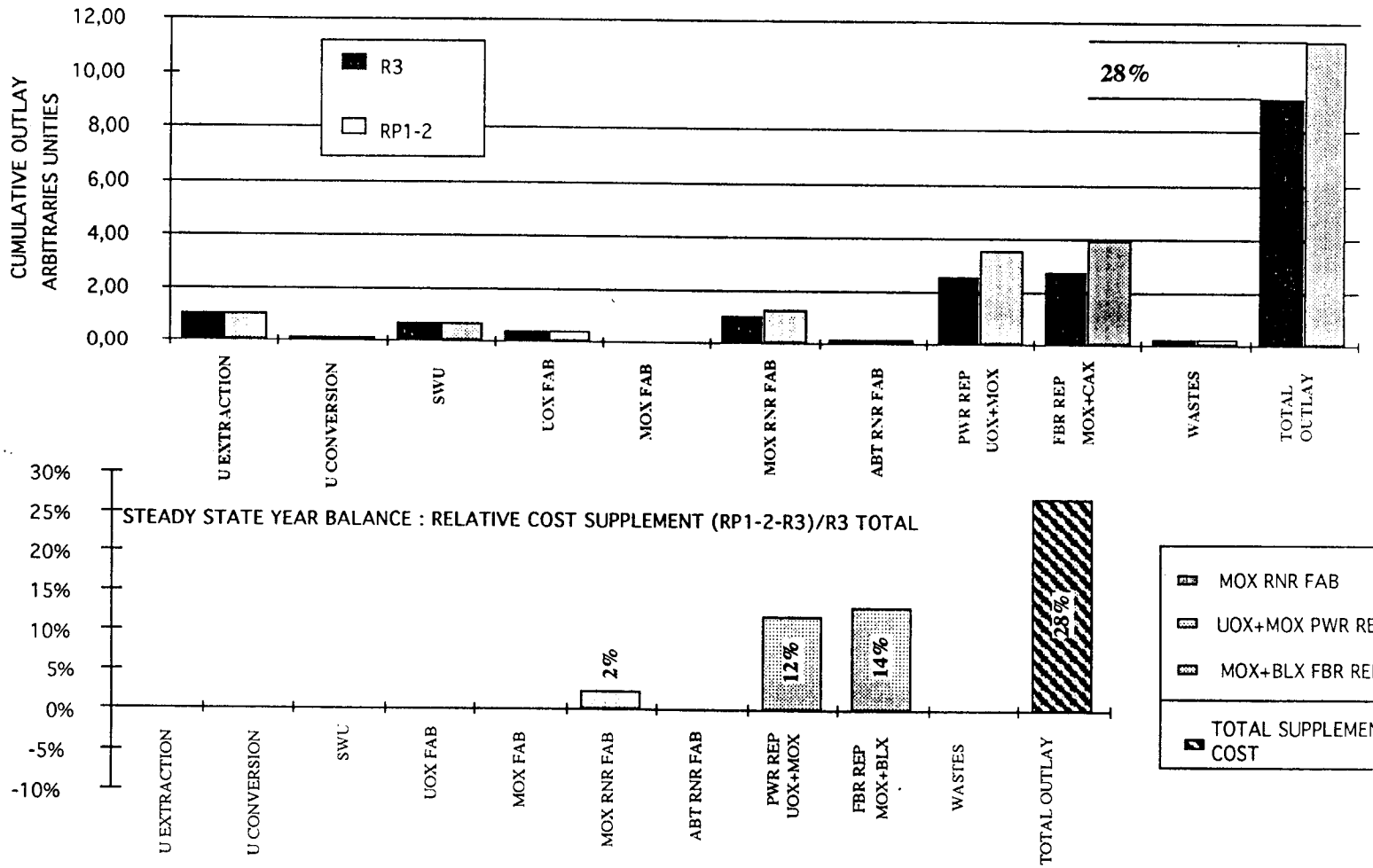


CEA **DCC/ DRDD/SSP**	ETUDE CCE : PARTITION / INCINERATION	DATE : JUL 94
	UNIT CYCLE OUTLAY DURING A TYPICAL STEADY-STATE OPERATING YEAR FOR SCENARIOS R2 AND RP1-1	**APPENDIX N° 6.1**

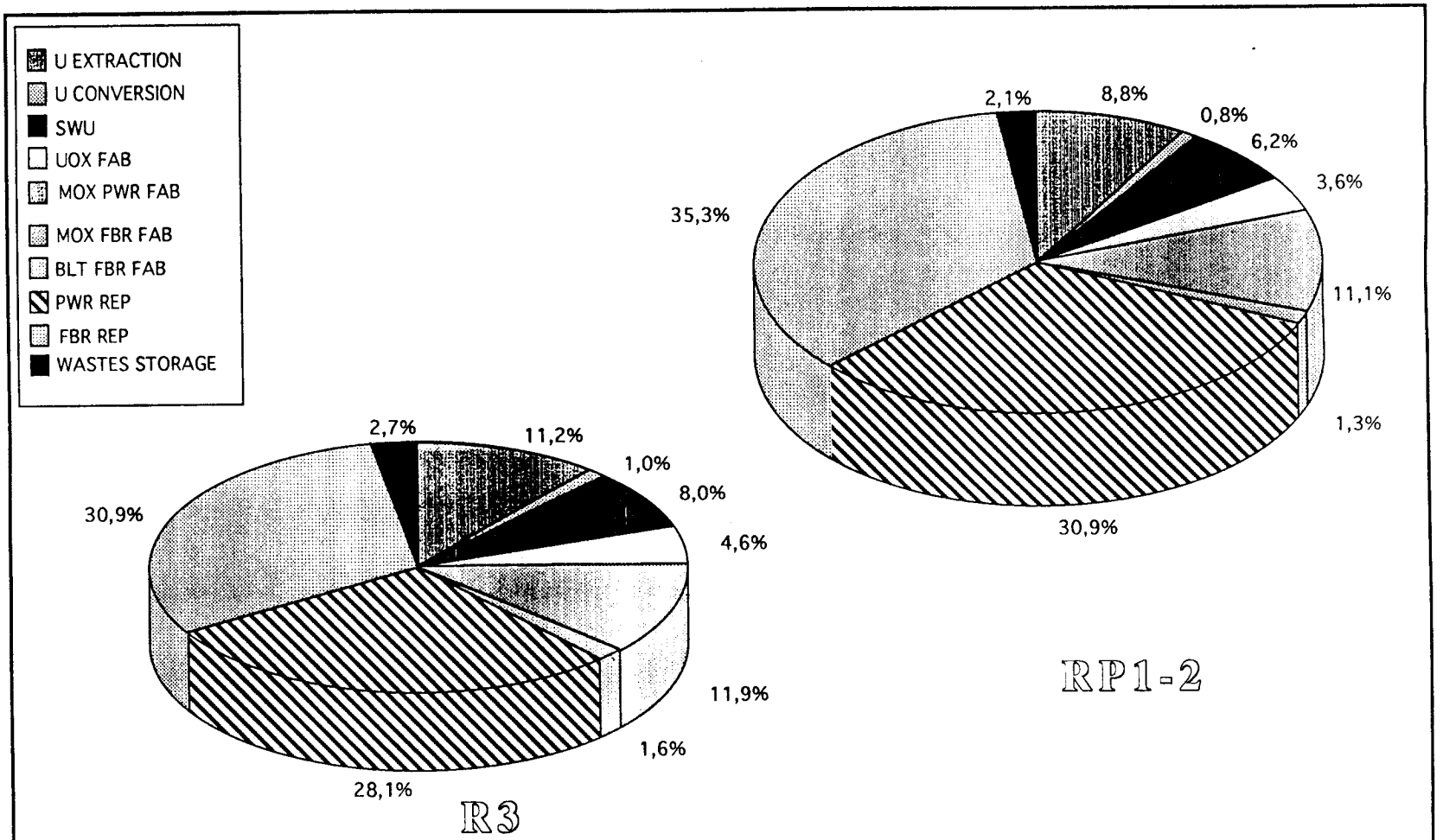




CEA DCC/DRDD/SSP	ETUDE CCE : PARTITION / INCINERATION		DATE : JUL 94
	UNIT CYCLE OUTLAY DURING A TYPICAL STEADY-STATE OPERATING YEAR FOR SCENARIOS R2 AND RP1.1		**APPENDIX N° 6.2**



CEA DCC/ DRDD/SSP	ETUDE : CCE PARTITION / INCINÉRATION	DATE : JUL 94
	UNIT CYCLE OUTLAY DURING A TYPICAL STEAD-STATE OPERATING YEAR FOR SCENARIOS R3 AND RP1.2	**APPENDIX N° 6.3**



CEA **DCC/DRDD/SSP**	ETUDE CCE : PARTITION / INCINERATION		DATE : JUL 94
	UNIT CYCLE OUTLAY DURING A TYPICAL STEADY-STATE OPERATING YEAR FOR SCENARIOS R3 AND RP1.2		**APPENDIX N° 6.4**