ORNL/TM-2004/179

FY 2002 AFCI Economic Study for Series 1 Near-Term Chemical Processing of LWR Spent Fuels and Fabrication of LWR MOX Fuel

September 2004

Prepared by

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Nuclear Science and Technology Division

FY 2002 AFCI ECONOMIC STUDY FOR SERIES 1 NEAR-TERM CHEMICAL PROCESSING OF LWR SPENT FUELS AND FABRICATION OF LWR MOX FUEL

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Date Published: September 2004

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Oak Ridge, Tennessee 37831-6283
managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
ATW	accelerator to waste
HLW	high-level waste
HTGR	high-temperature gas-cooled reactor
LLW	low-level waste
LWR	light-water reactor
MOX	mixed oxide
P-T	partitioning–transmutation
PWR	pressurized-water reactor

1. INTRODUCTION

In 2002, a report to Congress was written for the Advanced Fuel Cycle Initiative (AFCI) Program, outlining the goals for improvements in the disposal of spent nuclear fuels and describing an organized approach to accomplishing these objectives. The goals for the intermediate term were (1) to greatly extend the period of time before a second high-level-waste (HLW) repository would be needed by reducing the volume and heat load of HLW; (2) to avoid the substantial costs and social impacts associated with multiple future repositories; (3) to place the HLW into more durable storage forms, enabling reduction of release rates by orders of magnitude; and (4) to significantly reduce the radiotoxicity of HLW sent to the geologic repository. Accomplishment of these goals will enable the sustainability of nuclear power and growth in nuclear-generating capacity. A short quantitative economic study was made to determine if favorable economics could be achieved, and the results were made available for inclusion in the report to Congress.[1]

2. ASSUMPTIONS

Assumptions for the study were that industrial-scale facilities could be designed, built, put into operation by 2015, and operated for >30 years to process light-water-reactor (LWR) spent fuels from the current generating capacity [100 GW(e)]. Moreover, the study assumed that separations processes for the heat-generating fission products and long-lived actinides could be developed and used in the industrial-scale facilities. The baseline second repository cost was taken to be $35 billion, assuming that lessons learned could provide significant savings over the ~$60 billion cost of the first repository. Estimated costs for the back-end fuel-cycle cases evaluated were in constant 2002 dollars, without discount. A key assumption was that no financing costs were necessary. This assumption was made to enable the cost comparison of the base case (currently planned once-through LWR spent fuel to be sent to the repository) with the evaluated cases on an equal basis.

An overall material mass flow summary for all cases was developed (Fig. 1) to provide the entire processing flowsheet being developed at the time the study was done. The mass amounts were derived from ORIGEN2 calculations for pressurized-water-reactor (PWR) spent fuel that had been irradiated to 33 GWd/MT and cooled for 5 years. The volumes were estimated from the approximate bulk density of the chemical form (oxide, metal, glass, etc.) of the effluent material.

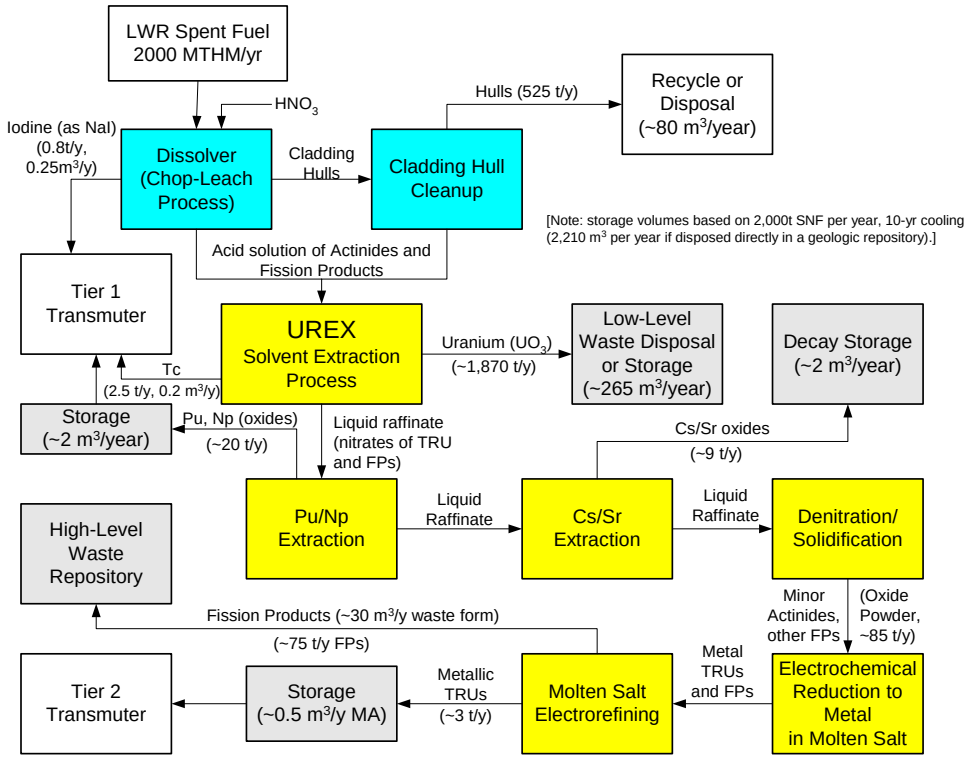

Fig. 1. Material mass flow summary.

The mass and volume estimates for the waste streams made it possible to determine the characteristics of the HLW that would require repository storage. In all cases, the largest effluent stream is the uranium—which can be decontaminated sufficiently to meet Class C low-level-waste (LLW) limits or reenriched and reused. The second-largest mass is the zircaloy cladding hulls, which will contain a small amount of residual fuel and the long-lived activation products, ^{93}Zr and ^{94}Nb. This waste will require compaction and repository storage unless an acceptable method of decontamination, reformulation, and reuse can be developed. In all cases, the heat-generating fission product elements (cesium and strontium) and their radioactive daughter isotopes would be isolated and solidified to permit more efficient storage in the repository. The remaining fission products (predominantly lanthanides and noble metals) would be encapsulated into an improved waste form, such as glass, for storage in the repository. In all cases, the volume of wastes requiring repository storage could be significantly reduced and the heat-generating wastes could be more efficiently managed such that the need for a second repository could be delayed significantly.

2.1 CASES EVALUATED

Three cases were evaluated for comparison of net costs with those of the currently planned once-through LWR spent fuel disposal to the repository:

1. Chemical processing of LWR spent fuel (2000 MT/year),
2. Chemical processing of LWR LEU spent fuel (2000 MT/year) and LWR mixed-oxide (MOX) fuel fabrication/irradiation (two cycles), and
3. Chemical processing of LWR spent fuel (2000 MT/year) and high-temperature gas-cooled reactor (HTGR) Pu-Np fuel fabrication/irradiation (one cycle).

For each case, (1) a process material mass flowsheet was developed, (2) the schedule necessary to meet the planned start of operation in 2015 was determined, and (3) the costs were estimated. The process flowsheets showed the specific process steps required, as well as the mass, volume, and radionuclide composition of the product and waste streams.

The schedule and economic analysis for each case showed the time and costs required for (1) completion of research and development, (2) environmental impact analysis, (3) site and contractor selection, (4) capital funding supply, (5) design, (6) construction, (7) licensing, and (8) startup operations. The minimum overall time required before startup was estimated to be ~13–15 years. Capital funding of $1 billion to $2 billion per year would be required during the 8-year design, construction, licensing, and startup period. For a 2015 startup, the initial capital funding would need to be available by 2007.

For each case, the estimated costs were determined, and opportunities for cost reduction (e.g., co-locating and integrating the chemical processing and fuel fabrication facilities) were identified. The estimated costs were based on (1) the Pacific Northwest National Laboratory Model for the Accelerator-to-Waste (ATW) Roadmap; (2) published costs of commercial reprocessing and fuel fabrication plants, escalated to 2002; (3) typical design cost distribution; (4) current prices for new UO_2 and MOX fuel assemblies; and (5) the process knowledge, experience, and judgment of the authors. The process material flowsheets, schedules, and cost estimates are given for Cases 1, 2, and 3, respectively, in Appendices A, B, and C.

One significant cost-reduction method was assumed to be applied to Cases 2 and 3: that is, the use of co-located and integrated chemical processing, fuel fabrication, and waste treatment/storage facilities to consolidate the plant infrastructure, maximize integration of process activities, and minimize storage and/or transportation costs.

As indicated in Table 1, significant cost savings were indicated for all three cases evaluated when compared with the cost of a second repository.

Table 1. Summary of comparative costs

	Cost ($B)		
	Case 1	Case 2	Case 3
Comparative cost of repository	35	35	35
Cost of back-end fuel cycle	20.6	12.0	14.9
Net cost savings	14.4	23.0	20.1

The costs for the back-end fuel-cycle cases evaluated did not include decommissioning costs. If these extra costs had been added, the net cost savings would have been reduced by relatively small amounts, but not significantly when considering the potential for overall cost savings.

2.2 NEW CONSIDERATIONS BASED ON AFCI STUDIES SINCE THE 2002 COST ESTIMATE

As indicated above, several significant cost-reduction methods were identified during the 2002 cost study. These included (1) co-location and integration of the spent fuel separations, fuel fabrication, and waste treatment facilities; (2) use of simplified process steps; and (3) maximized use of automated processes and robotic methods. Since the cost study, further cost reduction and technical capability improvements have been identified through ongoing R&D and deployment studies and are being developed.

Further cost reductions in both partitioning and transmutation were identified for processing "the oldest fuel first." This means that there will be a minimum of 30 years of decay storage for spent fuels.[2] The concept came from analyses of the situation in the United States, where untreated spent fuel has accumulated at reactor sites for >30 years. Significant reductions in radioactivity emissions and decay heat from the fission product radionuclides occur during these long decay periods. As a result, the separations processes can be simplified (fewer cycles of purification) and the volume and area of shielded facilities within the plant can be reduced.

Even more significant improvements in LWR transmutation occur because, during ≥ 30-year decay periods, more than 75% (>2 half-lives) of the ^{241}Pu isotope decays to ^{241}Am, and during the subsequent irradiation, the transmutation pathway is altered to minimize the production of ^{244}Cm and heavier nuclides and to produce increased amounts of fissionable plutonium isotopes.[3]

The alteration of the transmutation pathway enables multiple partitioning–transmutation (P-T) cycles to partition plutonium and the minor actinides (neptunium, americium, and curium) and to transmute them in existing and future thermal-spectrum LWRs. Thus, no capital investment for a special transmuter reactor (fast reactor or accelerator-driven system) is required.

The lifetime of the HLW repository will be extended significantly because all of the plutonium and minor actinides will be kept in process (separations, fuel fabrication, and irradiation in LWRs) or in wet and dry spent fuel storage. Thus, only fission products would be put into the repository. Moreover, because the number of spent fuel assemblies in inventory will remain the same after the P-T recycling begins, no new storage capacity will be needed for wet and dry spent fuel storage. Furthermore, efficient use of the fuel/target fabrication facilities can be obtained by routing the larger fraction of recycled nuclides (plutonium and neptunium) into conventional glove-box-contained MOX fuel fabrication and routing the smaller fraction (americium and curium) into shielded fabrication facilities. Thus, the volume and area of more expensive shielded facilities will be minimized.

Finally, significant simplification of the separations process steps and equipment has occurred since the 2002 cost study was made. Figure 2 illustrates the current state of development. When compared with the P-T system (Fig. 1) on which the 2002 cost study was based, many simplifications and cost reductions have been made possible and further improvements are being studied.

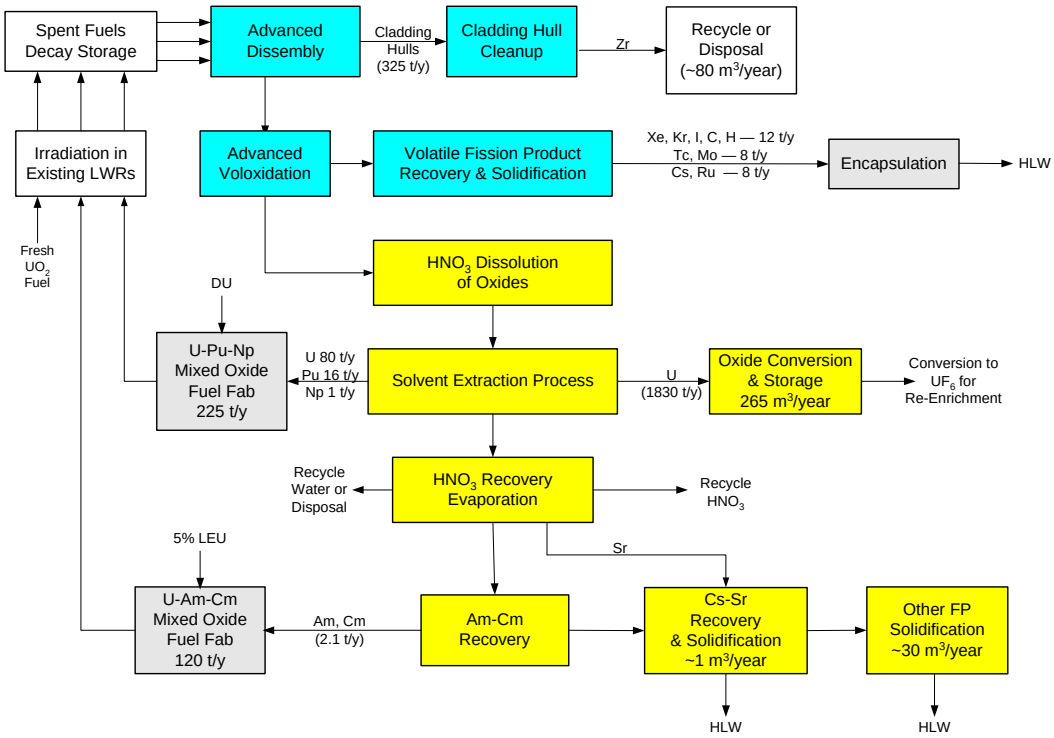

Fig. 2. Current status of material mass flow.

2.3 BRIEF COMPARISONS WITH OTHER COST STUDIES

Several cost studies[4,5] cite the effect of uranium prices on the fuel cycle. Uranium prices and availability will definitely determine when fast breeder reactors and plutonium-based fuels will need to be deployed. However, because of the relatively small amount (~1%) of plutonium and minor actinides in LWR-UO_2 spent fuels, only a small amount (~15%) of the fissile uranium needed for LWR fuel would be replaced by recycled plutonium if the back end of the LWR fuel cycle is closed. Thus, the proper basis for cost comparison is the capital and operating costs for a spent fuel separations/MOX fuel fabrication plant versus the cost of additional repositories. This was the basis of comparisons used in the 2002 AFCI Economic Study.

Capital cost estimations in the 2002 AFCI Economic Study and in other cost studies typically began with the ~$6 billion costs of the THORP and LaHague UP-3 plants. Estimates for scaling and for differing capabilities vary widely. In a recent AFCI study,[6] the effect of scale on capital costs was found to be small for plants with capacities up to 1500 MT/year while near-optimum-sized plant capacities were found to be in the range of 2000–10,000 MT/year. For a 2000 MT/year plant, capital cost estimates determined in that 2003 AFCI study were very similar to those estimates in the 2002 AFCI Economic Study.

When scaling factors are applied, operating cost estimates in reference studies[4,5] appear to have resulted in enormously high values that are not supported by the number of operating personnel that is practical for a well-designed and automated plant. The number and types of operating personnel estimated in a recent study by Washington Group International for the AFCI program[7] are much more practical and realistic when compared with staffing patterns at existing commercial plants.

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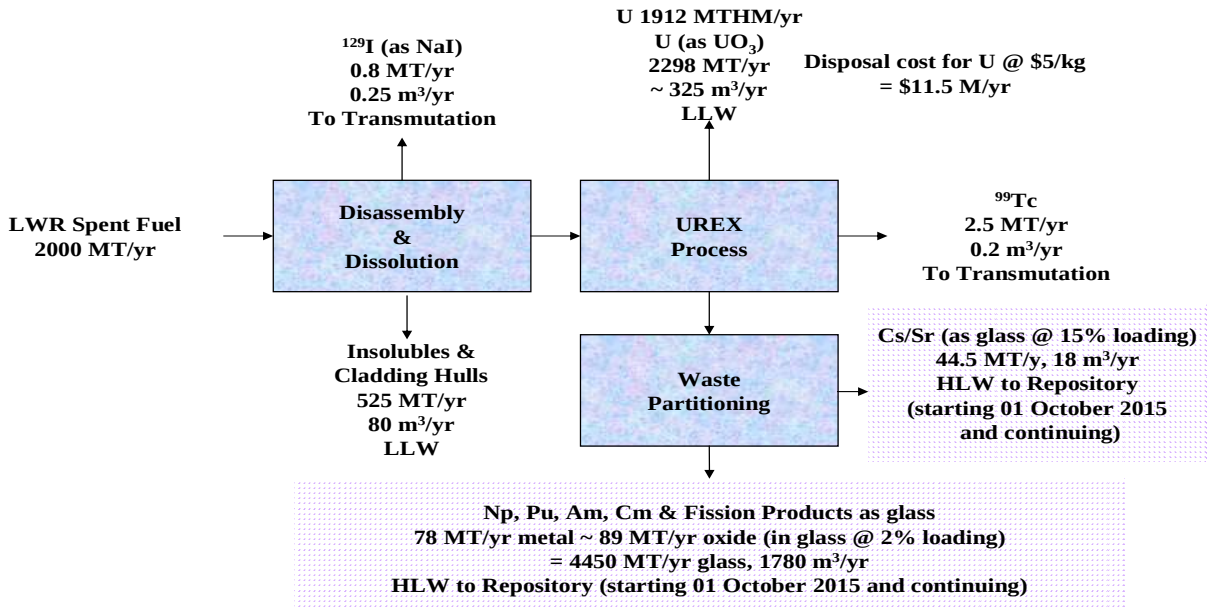
APPENDIX A

PROCESS MATERIAL MASS FLOWS



Case 2: Process Material Mass Flow

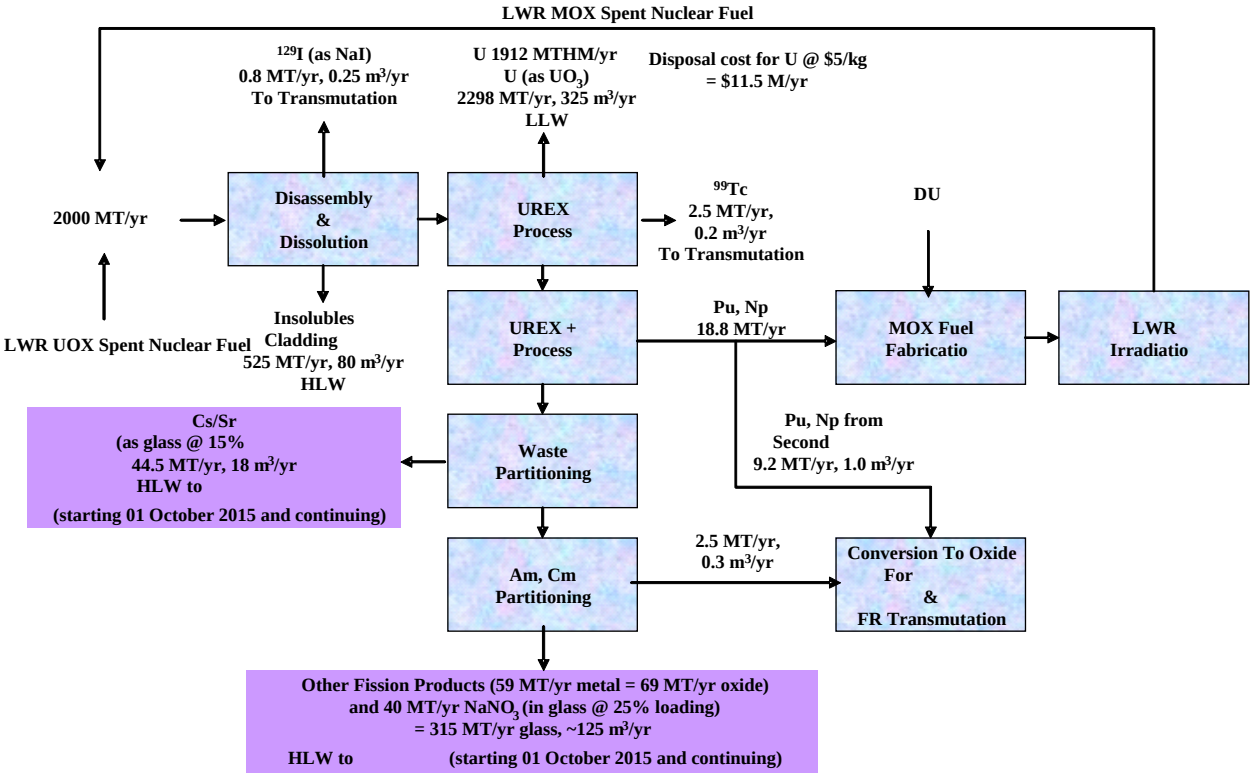


Fig. A.2. Case 2 — Process material mass flow.

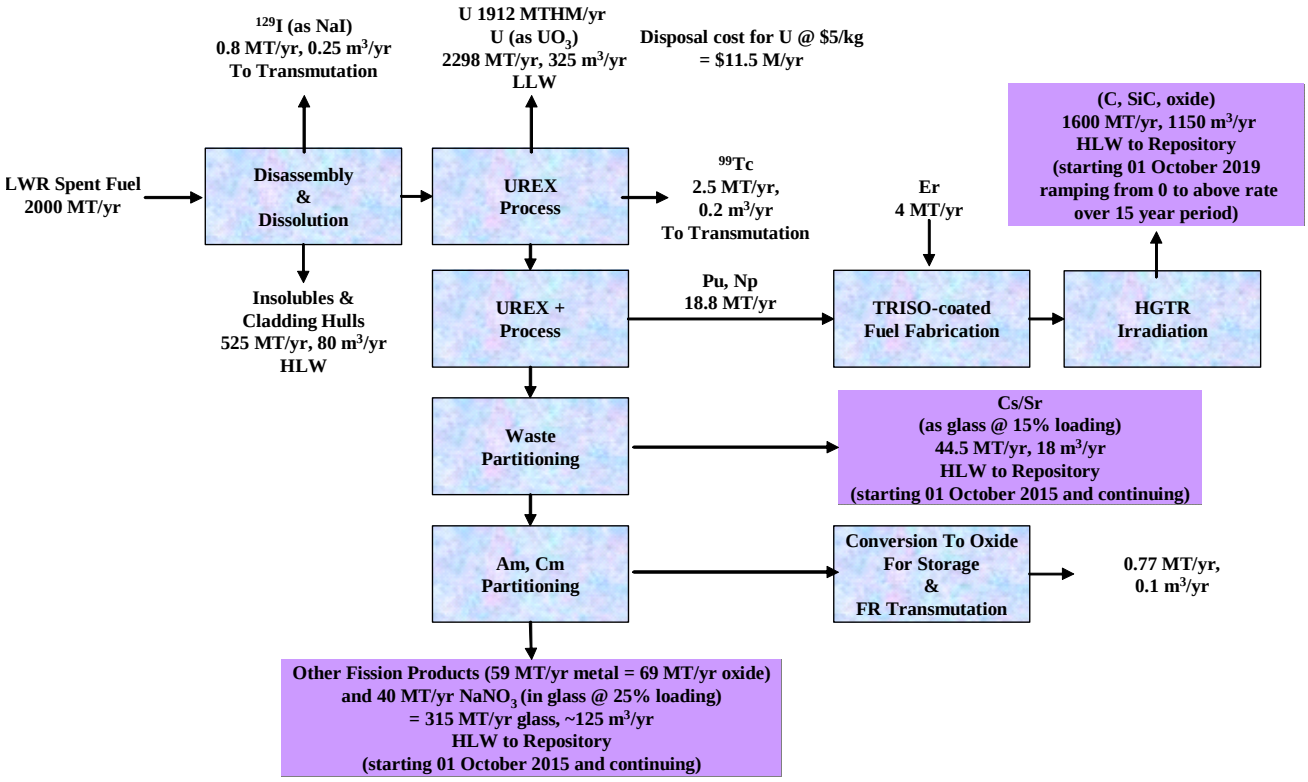


Fig. A.3. Case 3 — Process material mass flow.

APPENDIX B

SCHEDULES

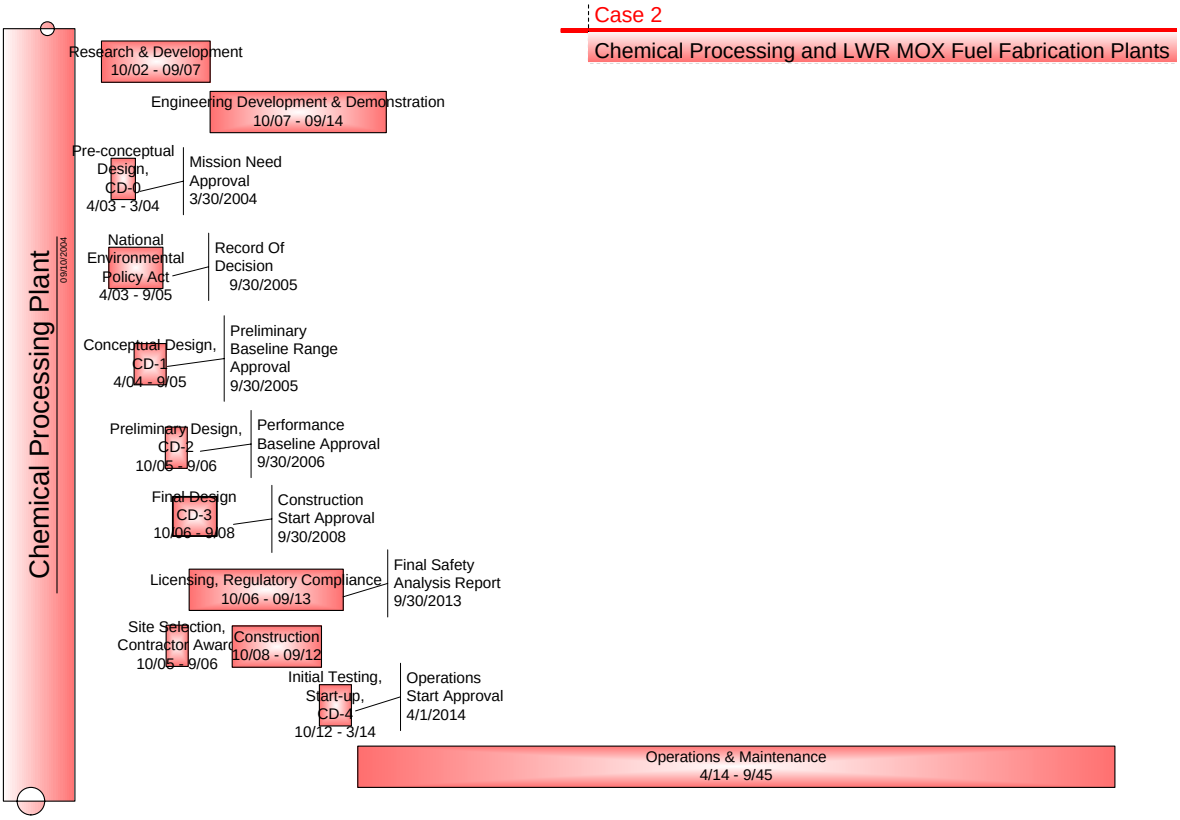


Fig. B.1. Case 1 — Chemical processing plant (2000 MT/year).

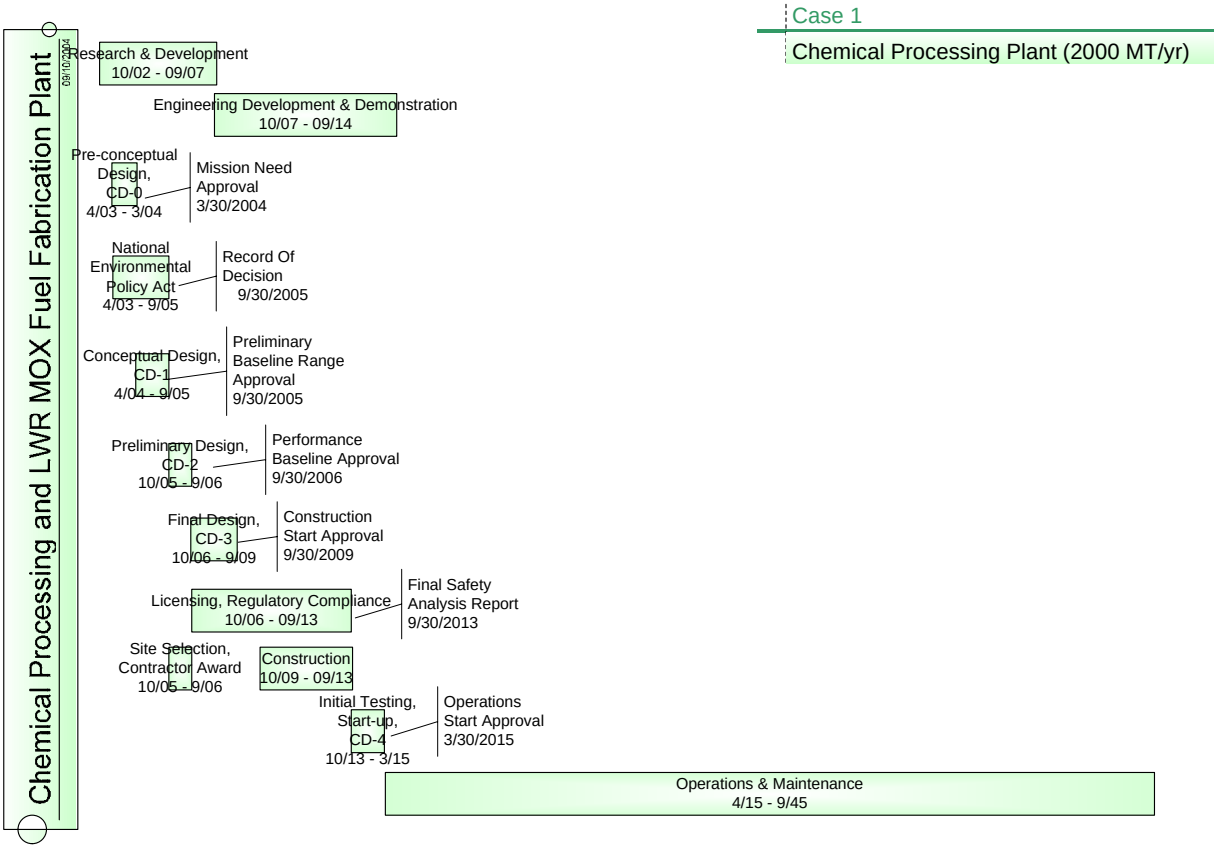


Fig. B.2. Case 2 — Chemical processing and LWR MOX fuel fabrication plants.

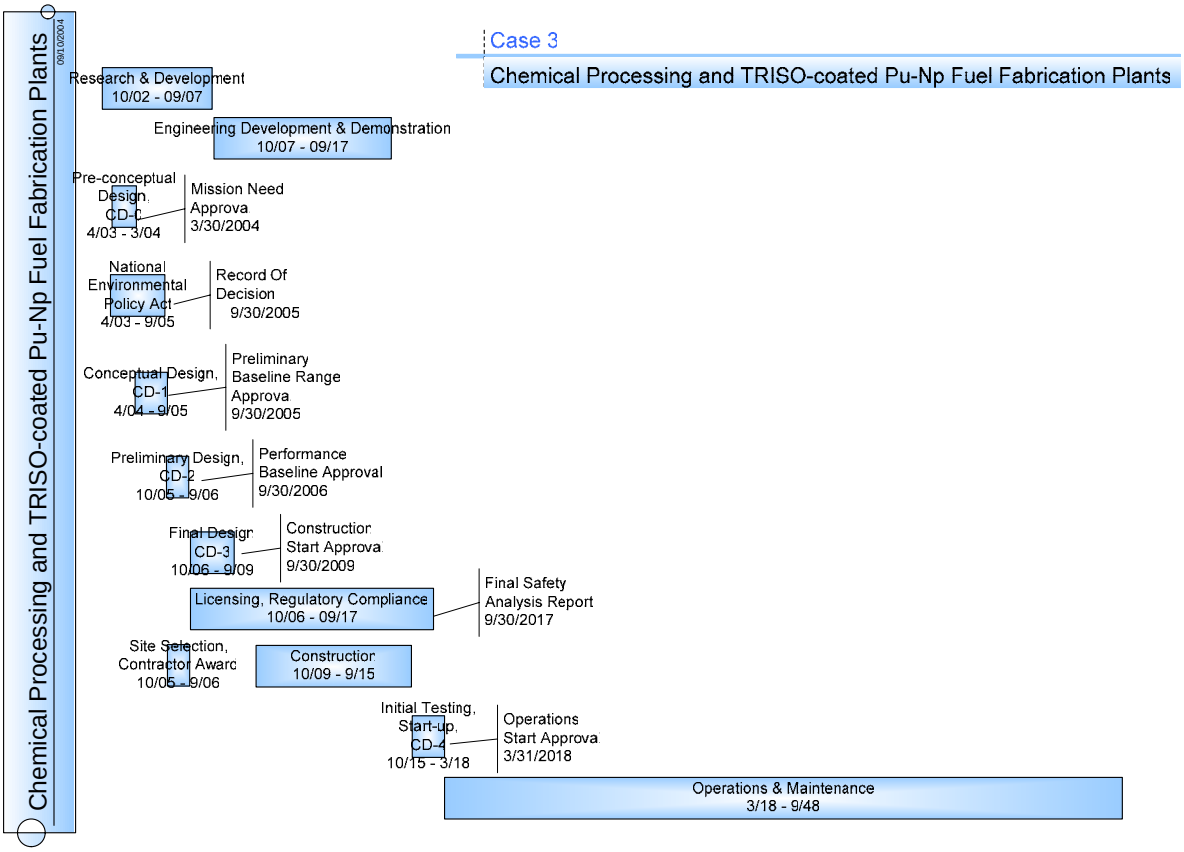


Fig. B.3. Case 3 — Chemical processing and TRISO-coated Pu-Np fuel fabrication plants.

APPENDIX C

COST ESTIMATES

Table C.1. Case 1 — Chemical processing plant

Activity	Time Period	Duration (y)	Estimated Cost $M/y	$M	Basis
Research & Development	10/02 - 9/07	5	9	46	FY 03 through FY 07; $6, 7, 11, 11, 11M
Engineering Development & Demonstration	10/07 - 9/14	8	40	320	FY 08 through FY 15; $30,40,45,45,45,45,40,30M
Preconceptual Design, CD-0	4/03 - 3/04	1	4	4	20 man-years; FY 03-FY 04
Mission Need Approval	3/30/2004				
NEPA Actions	4/03 - 9/05	2	2	4	20 man-years; FY 03-FY 05
Record of Decision	9/30/2005				
Conceptual Design, CD-1	4/04 - 9/05	1.5	11	16	80 man-years; FY 04-FY 05
Preliminary Baseline Range Approval	9/30/2005				
Site Selection, Contractor Award	10/05 - 9/06	1			
Licensing, Regulatory Compliance	10/06 - 9/13	7	2	14	
Final Safety Analysis Report	9/30/2013				
Preliminary Design, CD-2, Final Design, & CD-3	10/05 - 9/08	3	417	1250	1250 man-years; FY 07-FY 09; using PNNL cost estimating procedure for the ATW Roadmap, the design cost would be $285M
Construction Start Approval	9/30/2008				
Construction	10/08 - 9/12	4	1565	6250	Plant will operate with no TRU separations, but must be designed and built with capability to expand to more complete flowsheet; also includes vitrification plant. PNNL model for ATW Roadmap would estimate construction cost at $2.6B. Construction costs
Operations Start Approval	3/30/2014				
Initial Testing, Startup, CD-4	10/12 - 3/14	1.5	300	450	Based on 120% of estimated operations & maintenance costs
Other Project Costs (OPC)	4/03 - 3/14	12	183	2196	OPC (less ED&D, Conceptual Design, Licensing, NEPA and Start-up). Based upon the total OPC being ~40% of the TEC (Design + Construction).
Operations & Maintenance	4/14 - 9/45	30	250	7500	Assumed O&M staff of 1000 people at a combined rate of $250K per person/year = $250M/y. Process is limited. No TRU separation.
Incoming Transportation of Spent Fuel	3/14 - 9/44	30	17	510	170 shipments per year at $100K each
Outgoing Transportation of HLW to Repository	10/15 - 9/45	30	56	1680	560 shipments per year (5 logs each) at $100K per shipment
Outgoing Disposal of LLW	10/15 - 9/45	30	12	360	Uranium at $11.5M/y; other LLW at $0.5M/y.
Total Costs for Case 1		30	687	**20600**	
Comparative Costs of Repository		30	1167	35000	Includes costs of design, construction, licensing, and operation
Difference (Cost Savings)		30	480	**14400**	

Table C.2. Case 2 — Chemical processing and LWR MOX fuel fabrication plants

Activity	Time Period	Duration (y)	Estimated Cost $M/y	$M	Basis
Research & Development	10/02 - 9/07	5	9	46	FY 03 through FY 07; $6, 7, 11, 11, 11M
Engineering Development & Demonstration	10/07 - 9/14	8	40	320	FY 08 through FY 15; $30,40,45,45,45,45,40,30M
Preconceptual Design, CD-0	4/03 - 3/04	1	6	6	30 man-years; FY 03-FY 04
Mission Need Approval	3/30/2004				
NEPA Actions	4/03 - 9/05	2	3	6	30 man-years; FY 03-FY 05
Record of Decision	9/30/2005				
Conceptual Design, CD-1	4/04 - 9/05	2	12	24	120 man-years; FY 04-FY 05
Preliminary Baseline Range Approval	9/30/2005				
Site Selection, Contractor Award	10/05 - 9/06	1			
Licensing, Regulatory Compliance	10/06 - 9/13	7	2	14	
Final Safety Analysis Report	9/30/2013				
Preliminary Design, CD-2, Final Design, & CD-3	10/05 - 9/09	4	350	1400	1400 man-years; FY 07-FY 09; using PNNL cost estimating procedure for the ATW Roadmap, the design cost would be $430M
Construction Start Approval	9/30/2009				
Construction	10/09 - 9/13	4	1850	7400	Same basis as Case 1 except with integral design,construction, and licensing of chemical processing and MOX fuel fabrication plants within the same plant site with common physical safeguards protection, common utility services, laboratory facilities, etc.
Operations Start Approval	3/30/2015				
Initial Testing, Startup, CD-4	10/13 - 3/15	1.5	425	635	Based on 120% of estimated operations & maintenance costs
Other Project Costs (OPC)	4/03 - 3/15	12	218	2616	OPC (less ED&D, Conceptual Design, Licensing, NEPA and Start-up). Based upon the total OPC being ~40% of the TEC (Design + Construction).
Operations & Maintenance	4/15 - 9/45	30	353	10590	Based on cost of MOX fuel at $2000/kg fabricated fuel
Incoming Transportation of Spent Fuel	3/12 - 9/44	30	17	510	170 shipments per year at $100K each
Outgoing transportation of MOX fuel to reactors	10/15 - 9/45	30	2	45	30 shipments per year at $50K each
Outgoing Transportation of HLW to Repository	10/15 - 9/45	30	2	60	20 shipments per year (5 logs each) at $100K per shipment
Outgoing Disposal of LLW	10/15 - 9/45	30	12	360	Uranium at $11.5M/y; other LLW at $0.5M/y.
Total Costs for Case 2		30	801	24032	
Fuel replacement credit		30	-400	-12000	Replaces 400 t/y UOX fuel at $1000/kg
Net Costs for Case 2		30	401	**12032**	
Comparative Costs of Repository		30	1167	35000	Includes costs of design, construction,licensing, and operation
Difference (Cost Savings)		30	766	**22968**	

Table C.3. Case 3 — Chemical processing and TRISO-coated Pu-Np fuel fabrication plants

Activity	Time Period	Duration (y)	Estimated Cost $M/y	Estimated Cost $M	Basis
Research & Development	10/02 - 9/07	5	9	46	FY 03 through FY 07; $6, 7, 11, 11, 11M
Engineering Development & Demonstration	10/07 - 9/14	8	40	320	FY 08 through FY 15; $30,40,45,45,45,45,40,30M
Preconceptual Design, CD-0	4/03 - 3/04	1	6	6	30 man-years; FY 03-FY 04
Mission Need Approval	3/30/2004				
NEPA Actions	4/03 - 9/05	2	3	6	30 man-years; FY 03-FY 05
Record of Decision	9/30/2005				
Conceptual Design, CD-1	4/04 - 9/05	2	12	24	120 man-years; FY 04-FY 05
Preliminary Baseline Range Approval	9/30/2005				
Site Selection, Contractor Award	10/05 - 9/06	1			
Licensing, Regulatory Compliance	10/06 - 9/17	11	1.3	14	
Final Safety Analysis Report	9/30/2014				
Preliminary Design, CD-2, Final Design, & CD-3	10/05 - 9/08	3	350	1400	1400 man-years; FY 07-FY 09; using PNNL cost estimating procedure for the ATW Roadmap, the design cost would be $430M
Construction Start Approval	9/30/2008				
Construction	10/08 - 9/15	7	1200	8400	Same basis as Case 1 except with integral design,construction, and licensing of chemical processing and MOX fuel fabrication plants within the same plant site with common physical safeguards protection, common utility services, laboratory facilities, etc.
Operations Start Approval	4/1/2017				
Initial Testing, Startup, CD-4	10/15 - 3/17	1.5	360	540	Based on 120% of estimated operations & maintenance costs
Other Project Costs (OPC)	4/03 - 3/15	12	218	2616	OPC (less ED&D, Conceptual Design, Licensing, NEPA and Start-up). Based upon the total OPC being ~40% of the TEC (Design + Construction).
Operations & Maintenance	4/17 - 9/45	30	300	9000	Based on cost of MOX fuel at $2000/kg fabricated fuel
Incoming Transportation of Spent Fuel	3/18 - 9/48	30	17	510	170 shipments per year at $100K each
Outgoing transportation of MOX fuel to reactors	10/19 - 9/49	30	2	45	30 shipments per year at $50K each
Outgoing Transportation of HLW to Repository	10/19 - 9/49	30	2	60	20 shipments per year (5 logs each) at $100K per shipment
Outgoing Disposal of LLW	10/19 - 9/49	30	12	360	Uranium at $11.5M/y; other LLW at $0.5M/y.
Total Costs for Case 3		30	778	23347	
Fuel replacement credit		30	-282	-8460	Replaces average of 282 t/y UOX at $1000/kg due to need to ramp up GCRs
Net Costs for Case 3		30	496	**14887**	
Comparative Costs of Repository		30	1167	35000	Includes costs of design, construction,licensing, and operation
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