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FUEL CYCLE COST STUDIES — FABRICATION, REPROCESSING, AND REFABRICATION OF LWR, SSCR, HWR, LMFBR, AND HTGR FUELS

A. R. Olsen, R. R. Judkins, W. L. Carter, and J. G. Delene

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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A. R. Olsen, R. R. Judkins, W. L. Carter,* J. G. Delene†

ABSTRACT

The comparative analysis of power generation costs for the various reactor cycles that is being performed in the Nonproliferation Alternative Systems Assessment Program (NASAP) and the International Nuclear Fuel Cycle Evaluation (INFCE) requires that the costs associated with processing of fuel materials for use in these cycles be estimated. The study described here provided unit cost estimates for the fabrication, reprocessing, and refabrication of a variety of fuels for several reactor systems.

We examined in detail the facility requirements and operations to estimate capital and operating costs. Unit processing cost determinations were based on a cash flow analysis technique in which income from sales over the life of each facility was equated to the total capital and operating expenses of that facility plus a specified return on equity investment. The effects of plant capacities were determined by application of scaling factors to individual components of the reference plant costs.

Capital and operating costs were estimated for 21 reactor and fuel cycle combinations. Based on these estimates, unit costs were determined for fabrication, reprocessing, and refabrication of the fuels. In each instance, the effect of plant capacities on unit costs associated with the processing of fuels was determined. All costs were based on mature industries, and first-of-a-kind costs were not included.

Unit cost determinations were based on three financing techniques, which included government financing, typical industrial financing, and high-risk industrial financing. The unit costs recommended for the comparative analysis of power generation costs are those associated with the economic assumptions of a typical industry.

INTRODUCTION

This report presents economic analyses and cost estimates for fuel fabrication, fuel reprocessing (including product conversion), and fuel

*Chemical Technology Division.
†Engineering Technology Division.

refabrication for several reactor and fuel cycle combinations that are being considered in the Nonproliferation Alternative Systems Assessment Program (NASAP) and the International Nuclear Fuel Cycle Evaluation (INFCE). The particular reactors and fuel cycles for which cost estimates were made include all those under consideration in the NASAP and the INFCE Working Group 5 (WG/5) fast breeder reactor fuel cycle options at the time of this study. These reactors and fuel cycles are identified in Table 1.

Table 1. Summary of Reactor and Fuel Cycle Combinations

Reactor[a]	Initial Fuel	Recycle Fuel
LWR, SSCR	$(^{235}U,U)O_2$	$(Pu,U)O_2$
	$(^{235}U,Th)O_2$	$(^{233}U,Th)O_2$
	$(Pu,Th)O_2$	$(^{233}U,U)O_2$ or $(^{233}U,Th)O_2$
HWR	UO_2 (Natural)	
	$(^{235}U,U)O_2$	$(Pu,U)O_2$
	$(^{235}U,Th)O_2$	$(^{233}U,Th)O_2$
	$(Pu,Th)O_2$	$(^{233}U,U)O_2$ or $(^{233}U,Th)O_2$
LMFBR		
Core	$(^{235}U,Th)O_2$	$(^{233}U,Th)O_2$
	$(Pu,U)O_2$	$(Pu,U)O_2$
	$(Pu,Th)O_2$	$(Pu,Th)O_2$ or $(^{233}U,Th)O_2$
	$(Pu,U)C$	$(Pu,U)C$
	$(Pu,Th)C$	$(^{233}U,Th)C$
	Pu,U,Zr	Pu,U,Zr
	Pu,Th	^{233}U,Th
Radial Blanket	UO_2	
	ThO_2	
	UC	
	ThC	
	U	
	Th	
HTGR	$^{235}UC_2,ThO_2$	$^{233}UC_xO_y,ThO_2$
	$[(^{235}U,U)C_2,$ $(^{235}U,U,Th)O_2,$ $ThO_2]$	$[(^{233}U,U)O_2,$ $(^{235}U,U,Th)O_2,$ $ThO_2]$
	$(^{235}U,U)C_2$	
	PuO_2,ThO_2	$^{233}UC_xO_y,ThO_2$

[a]LWR, Light-Water Reactor; SSCR, Spectral Shift Control Reactor; HWR, Heavy-Water Reactor; LMFBR, Liquid-Metal-Cooled Fast Breeder Reactor; HTGR, High-Temperature Gas-Cooled Reactor.

The cost estimates presented represent an update and extension of similar cost estimates that were initially prepared[1] in 1976 for the Thorium Assessment Program and updated[2] as part of the DOE Studies and Evaluations Program to provide the NASAP provisional data base in 1977. The cost estimates are based on mature industries and do not include first-of-a-kind costs.

Unit prices were determined for three different types of financing: government financing, typical industrial financing, and high-risk industrial financing. The resultant price ranges compare not only costs of different reactor and fuel cycle combinations, but also costs based on the different financing arrangements that may be available or that may apply to those countries participating in the INFCE. For the purpose of cost-benefit studies, the unit costs recommended for comparison of the various fuel cycles are those based on financing appropriate for a conventional risk industry; that is, typical industrial financing.

With the exception of light-water reactor low-enriched uranium (LEU) fuel fabrication, none of the systems considered has achieved full domestic commercialization or development. Hence, there is a degree of cost uncertainty as there is with any new energy technology. The range of uncertainty shown in the estimates is based on the estimators' technical experience and judgment and on current criteria and regulatory guidelines. The current uncertainty ranges are ±25% or smaller, depending upon the specific cost factor. However, actual costs may vary over much broader ranges. As any system becomes commercialized, improvements in technology or deficiencies in the technology may be discovered; environmental, safety, occupational, or safeguards regulations may become more stringent or may be relaxed; and the institutional context in which systems may be deployed could change. The commercial costs of any of these systems may deviate (higher or lower) from the current estimates and may fall outside the current uncertainty ranges. The number of digits used in the presentation of estimates is a result of the algorithm used and does not suggest the degree of accuracy of the estimates.

Other factors could also contribute to changes in the costs. Deviation from plant capacities could result from technical problems or from changes in regulatory criteria. Costs for plant sizes other than the reference size plants are estimated by using scaling factors. A wide range of opinion exists relative to appropriate scaling factors, and further study of these factors is under way.

The costs presented in this report represent only those associated with the actual processing and support operations performed in the respective plants. Costs of fuel materials (ore, refining, enrichment, etc.) are not included nor are the costs of transportation and waste disposal. For example, plutonium costs for use, loss, or disposal can be of particular significance for breeder fuels. These costs may significantly influence overall fuel cycle costs and should be considered in evaluation of specific fuel cycles.

Specific designs of fuel elements have significant effects on hardware costs and on the number of units handled in various functional areas in fabrication and refabrication plants. Fuel element designs considered in this study were based on available NASAP and INFCE data. The use of different or optimized designs could result in significant changes in unit costs for specific fuels, especially those not sufficiently developed to assure equivalence with standard fuel types.

Finally, selection of the mode of financing can have a large impact on unit costs. Estimates for three types of financing have been calculated and are intended to represent a wide range of possibility. It is recommended that when costs are presented that the types of financing be defined as indicated below and that no one type be represented as being most likely.

1. Government Financing. The fixed charge rate (FCR) for government financing assumes government ownership of facilities and financing based on government bond rates.

2. Typical Industrial Financing. The FCR for typical industry financing is typical of the financial structure of large chemical or petroleum companies.

3. High-Risk Industry Financing. The FCR for high-risk industry financing is representative of private commercial vendors' approach to new and risky ventures.

Although a broad range of opinion exists as to the most appropriate costs for fuel fabrication and reprocessing, these costs represent a relatively small component of total power costs. The level of uncertainty of generating plant capital costs and the long-term costs of uranium are generally larger than the ranges for fabrication and reprocessing costs. Nevertheless, fuel cycle costs will be important in the eventual commercialization of alternative fuel cycles, especially for those who must make the investment decisions to build the necessary facilities.

PLANT DESIGN AND ECONOMIC ANALYSIS ASSUMPTIONS

To assure consistency in the cost estimates for the large number of reactor types and fuel cycles considered in this study, some basic assumptions were made relative to the designs of the various plants and economic analysis methods for the unit cost assessments. These assumptions were based on meetings with INFCE Working Group 5 (WG/5) participants, personnel from Hanford Engineering Development Laboratory (HEDL), and Alternative Fuel Cycle Evaluation Program (AFCEP) participants. Plant design assumptions are given in Table 2 and unit cost assessment assumptions are given in Table 3.

COST ESTIMATION PROCEDURES

The following sections outline the methods that were used to obtain the basic cost estimates for fuel reprocessing, fabrication, and refabrication. Details of the cost estimation methodologies for fuel reprocessing and fuel fabrication or refabrication are described in separate reports.[3,4]

Fuel Reprocessing

Cost estimates for reprocessing of specific fuels can be complicated by a number of details, including the type of fuel element and the

Table 2. Design Assumptions for Fabrication, Reprocessing, and Refabrication Plant Cost Analyses

Reference plant capacity:	
fabrication — 2 MTHM[a]/d	
reprocessing — 5 MTHM/d	
refabrication — 2 MTHM/d	
Effective full-production days per year:	
reprocessing — 300	
fabrication — contact operation — 260	
refabrication — noncontact operation — 240	
On-site storage at fabrication, reprocessing, and refabrication plant:	30 d
Cooling time before reprocessing: 180 d	
Fabrication, reprocessing, and refabrication shall be in separate facilities.	
Blanket material (U,Th) is to be recovered.	
Licensing requirements are current NRC-ALARA[b] criteria.	
Design criteria for shielding: 0.25 mR/h (18 pA/kg) at outside surface.	

[a]MTHM: metric tons of heavy metal.

[b]ALARA: as low as reasonably achievable.

required degree of separation of fuel components from each other and from fission products. To facilitate the preparation of the estimates, a set of generic cost estimates for various functional areas in the reprocessing plants was prepared. These estimates were based on analyses of specific process flowsheets of the several functional areas. Each functional area was evaluated to determine special requirements and costs, equipment costs and operating costs. The basic cost units were adjusted according to mass flow data and reprocessing requirements for each reactor and fuel cycle. These adjusted cost units were then integrated to provide the cost estimates for specific fuel cycles.

Fuel Fabrication and Refabrication

The cost estimation procedures for fuel fabrication and refabrication are not amenable to the development of generic functional area base cost numbers for a variety of reasons.

Table 3. Unit Cost Assessment Assumptions

	Value for Each Type of Financing		
	Government	Typical Industrial	High Risk Industrial
Project life, years			
Construction period	6	6	6
Operating period	20	20	20
Decommissioning period	3	3	3
Capital structure			
Equity, %	0	65	100
After-tax return on equity, %/year	0	14	15
Debt, %	100	35	0
Interest rate on debt, %/year	7.5	8.3	0
Weighted average cost of money, %/year	7.5	12.0	15.0
Taxes			
Federal income, %	0	48	48
State income, %	0	3	3
Property taxes and insurance, %	0	3	3
Federal investment tax credit, %	0	7	7
Tax depreciation method		SYD[a]	SYD[a]
Tax depreciation life, years		16	16
Equipment replacement and maintenance charge, % of initial equipment cost/year	5	5	5
Charge rate during construction, %/year	7.5	10.5	10.5
On-stream efficiency, %			
Years 1–6	0	0	0
Year 7	33	33	33
Year 8	67	67	67
Years 9–26	100	100	100
Owner's cost during construction (% of annual operating cost)			
Year 1	5	5	5
Year 2	10	10	10
Year 3	20	20	20
Year 4	30	30	30
Year 5	40	40	40
Year 6	40	40	40
Capital costs (% of total)			
Year 1	2.5	2.5	2.5
Year 2	6.5	6.5	6.5
Year 3	18.2	18.2	18.2
Year 4	44.2	44.2	44.2
Year 5	27.1	27.1	27.1
Year 6	1.5	1.5	1.5
Derived fixed charge rate, R[b]	0.108	0.226	0.316
Charges during construction, fraction of total cost			
Capital expenditures, I_c	0.249	0.366	0.366
Owner's cost, I_o	0.209	0.303	0.303

[a]Sum of years digits.

[b]Derived from a discounted cash flow analysis.

The primary factors affecting fabrication cost estimates are associated with the types of fissile and fertile materials, which can change the basic nature of the plant from contact operation and maintenance to remote operation and maintenance. Criticality considerations limit processing batch and lot sizes and equipment throughput rates. Operator protection and material properties, such as the pyrophoricity of carbides and metals, affect containment characteristics and operating atmosphere requirements. The specific designs of the fuel elements have significant effects on hardware costs and the number of units handled in the various functional areas. Consequently, cost estimates for the fuel fabrication processes were made individually for each reactor and fuel type. Specific fuel element designs were derived from available NASAP and INFCE data. Design data for these fuel elements are given in Appendix A. The reader is cautioned not to extrapolate the cost estimates to significantly different designs.

The cost estimation involved a detailed assessment of the space requirements for major equipment in each functional and process support area, estimation of costs for each set of equipment, determination of hardware and expendable materials costs, and an analysis of the facility manning and operating requirements. This was repeated for each reactor and fuel combination. The procedure used was based on that used[5] in estimating the fuel fabrication cost for a reference pressurized water reactor case.

Unit Cost Economic Analysis

The unit fabrication, reprocessing, and refabrication costs are obtained by use of the unit price analysis formula presented in Table 4. This formula is based on a discounted cash flow analysis, which provides for recovery of all capital and operating expenses (plus a return on investment for industrial financing) by establishing a levelized price for the sale of the fuel. Thus, the total income from sales of fuel over the life of a plant will just equal the total expenditures plus any specified return on investment.

Table 4. Unit Price Analysis Formula,

$$\$/kg = [(C_D + C_O + C_C)R + O + M + E_R + D]/T$$

where:[a]

C_D	=	facility plus equipment costs, $C_F + C_E$
C_F	=	facility cost (excluding process equipment)
C_E	=	equipment cost
C_O	=	owner's cost during construction
C_C	=	charge on direct capital during construction, $I_O C_O + I_D C_D$
I_D	=	fractional charge on design and construction cost during construction
I_O	=	fractional charge on owner's cost during construction
R	=	annual fixed charge rate on capital, fraction per year
O	=	annual operating cost
M	=	annual hardware and expendable material cost
A_R	=	annual maintenance and replacement rate on equipment, fraction per year
E_R	=	annual maintenance and replacement cost, $A_R C_E$
D	=	annual payment to establish fund for decommissioning
T	=	annual throughput achieved, Gg/year, XF
X	=	design capacity of plant, Gg/year
F	=	average fraction of design capacity achieved

[a]All costs in millions of dollars.

The unit costs obtained by use of the unit price analysis formula are given in terms of constant dollars as of January 1, 1978. Thus, the effects of escalation are not considered in these analyses. The estimated costs and costs that were derived from the information provided in Table 4 are summarized in Tables 5 through 10.

The costs presented in Tables 5 through 10 represent the summation of cost estimates for the various process areas. These costs have not been rounded, so the absolute accuracy of the estimates should not be inferred from the tables. All unit costs calculated by use of the formula in Table 4 are rounded to the nearest \$10 except that unit costs less than \$100/kg HM are rounded to the nearest \$5. The estimated accuracy of these unit costs is ±10% for contact operations and ±25% for remote operations.

REFERENCE PLANT UNIT COST ESTIMATES

The cases for which estimates were made and the associated costs for the reference capacity plants are summarized in this section. As indicated in Table 2, the reference capacities are 5 MTHM/d (1500 MTHM/year) for the reprocessing plants and 2 MTHM/d or 520 MTHM/year for contact operated and 480 MTHM/year for remotely operated fabrication and refabrication plants.

Unit cost estimates for reprocessing are presented in Table 11. Reprocessing costs include conversion of the product material to a shippable solid and the treatment of all waste for disposal. Shipping costs and disposal costs are not included. These costs are to be supplied by others.

The reference plant unit cost estimates for fabrication and refabrication are given in Tables 12 through 16. All fuel cycles for a given reactor type are presented in a single table except for the fast breeder reactor. For this case, the core assembly cost estimates are in one table and the radial blanket assembly cost estimates are in a second table. This approach was taken because design data are from two sources. The estimates, as stated earlier, depend on design and are based

Table 5. Summary of Estimated and Derived Costs for Reprocessing of LWR, SSCR, HWR, LMFBR, and HTGR Fuels

Fuel Cycle Case[a]	Economic Set[b]	Estimated Costs ($\$10^6$): Facility Cost ($C_F$)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Derived Costs ($\$10^6$): Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
LWR/SSCR									
$(Pu,U)O_2$/PF	A	660	255	3 3	29 9	43 4	236 9	12 8	1 4
	B	660	255	3 3	30 3	43 9	348 2	12 8	1 4
	C	660	255	3 3	30 5	44 3	348 3	12 8	1 4
$(Pu,U)O_2$/CL	A	643	245	3 2	29 3	42 5	230 0	12 3	1 4
	B	643	245	3 2	29 7	43 0	338 0	12 3	1 4
	C	643	245	3 2	29 9	43 3	338 1	12 3	1 4
$(U,Th)O_2$/PF	A	681	281	3 5	32 1	46 5	249 3	14 1	1 5
	B	681	281	3 5	32 4	47 0	366 3	14 1	1 5
	C	681	281	3 5	32 7	47 4	366 5	14 1	1 5
$(U,Th)O_2$/CL	A	653	271	3 4	31 4	45 6	239 6	13 6	1 5
	B	653	271	3 4	31 8	46 1	352 2	13 6	1 5
	C	653	271	3 4	32 1	46 5	352 3	13 6	1 5
HWR									
$(Pu,U)O_2$/PF	A	653	265	3 3	30 5	44 3	237 8	13 3	1 4
	B	653	265	3 3	30 9	44 8	349 6	13 3	1 4
	C	653	265	3 3	31 1	45 2	349 7	13 3	1 4
$(Pu,U)O_2$/CL	A	636	255	3 3	29 8	43 2	230 9	12 8	1 4
	B	636	255	3 3	30 2	43 8	339 4	12 8	1 4
	C	636	255	3 3	30 4	44 1	339 5	12 8	1 4
$(U,Th)O_2$/PF	A	689	275	3 4	31 3	45 4	249 5	13 8	1 4
	B	689	275	3 4	31 7	46 0	366 8	13 8	1 5
	C	689	275	3 4	32 0	46 4	366 9	13 8	1 5
$(U,Th)O_2$/CL	A	661	265	3 3	30 7	44 6	239 9	13 3	1 4
	B	661	265	3 3	31 1	45 1	352 6	13 3	1 4
	C	661	265	3 3	31 4	45 5	352 7	13 3	1 4
LMFBR									
$(Pu,U)O_2,UO_2$/PF	A	670	259	3 3	29 9	43 4	240 4	13 0	1 4
	B	670	259	3 3	30 3	43 9	353 3	13 0	1 4
	C	670	259	3 3	30 5	44 3	353 4	13 0	1 4
$(Pu,U)O_2,UO_2$/CL	A	653	249	3 2	29 3	42 5	233 5	12 5	1 4
	B	653	249	3 2	29 7	43 0	343 2	12 5	1 4
	C	653	249	3 2	29 9	43 3	343 3	12 5	1 4
$(U,Th)O_2,ThO_2$/PF	A	681	275	3 4	31 6	45 9	247 6	13 8	1 5
	B	681	275	3 4	32 0	46 4	364 0	13 8	1 5
	C	681	275	3 4	32 3	46 8	364 1	13 8	1 5
$(U,Th)O_2,ThO_2$/CL	A	653	265	3 4	30 9	44 9	238 0	13 3	1 4
	B	653	265	3 4	31 3	45 4	349 7	13 3	1 4
	C	653	265	3 4	31 6	45 8	349 9	13 3	1 5
(Pu,U)C,UC/PF	A	741	311	3 7	33 7	48 8	272 2	15 6	1 6
	B	741	311	3 7	34 1	49 4	400 0	15 6	1 6
	C	741	311	3 7	34 4	49 8	400 1	15 6	1 6

Table 5. (Continued)

Fuel Cycle Case[a]	Economic Set[b]	Estimated Costs ($\$10^6$)				Derived Costs ($\$10^6$)			
		Facility Cost (C_F)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
(Pu,U)C,UC/CL	A	724	301	3 6	33 1	48 0	265 2	15 1	1 5
	B	724	301	3 6	33 5	48 5	389 9	15 1	1 5
	C	724	301	3 6	33 8	48 9	390 0	15 1	1 6
(U,Th)C,ThC/PF	A	752	317	3 7	34 0	49 3	276 5	15 9	1 6
	B	752	317	3 7	34 4	49 9	406 4	15 9	1 6
	C	752	317	3 7	34 7	50 3	406 5	15 9	1 6
(U,Th)C,ThC/CL	A	724	307	3 6	33 4	48 4	266 8	15 4	1 5
	B	724	307	3 6	33 8	49 0	392 2	15 4	1 6
	C	724	307	3 6	34 1	49 4	392 3	15 4	1 6
Pu,U,Zr U/PF	A	680	276	3 4	31 3	45 4	247 5	13 8	1 4
	B	680	276	3 4	31 7	46 0	363 8	13 8	1 5
	C	680	276	3 4	32 0	46 4	363 9	13 8	1 5
Pu,U,Zr,U/CL	A	663	266	3 3	30 7	44 6	240 6	13 3	1 4
	B	663	266	3 3	31 1	45 1	353 7	13 3	1 4
	C	663	266	3 3	31 4	45 5	353 8	13 3	1 4
U,Th,Th/PF	A	691	284	3 5	32 1	46 5	252 5	14 2	1 5
	B	691	284	3 5	32 4	47 0	371 1	14 2	1 5
	C	691	284	3 5	32 7	47 4	371 2	14 2	1 5
U,Th,Th/CL	A	663	274	3 4	31 4	45 6	242 8	13 7	1 5
	B	663	274	3 4	31 8	46 1	356 9	13 7	1 5
	C	663	274	3 4	32 1	46 5	357 0	13 7	1 5
HTGR									
R-1, ^{235}MEU/Th	A	886	396	4 0	36 4	52 8	330 3	19 8	1 7
	B	886	396	4 0	36 9	53 5	485 4	19 8	1 7
	C	886	396	4 0	37 2	53 9	485 6	19 8	1 7
R-2, ^{233}MEU/Th	A	792	345	3 9	35 9	52 1	294 0	17 3	1 7
	B	792	345	3 9	36 4	52 7	432 1	17 3	1 7
	C	792	345	3 9	36 7	53 2	432 3	17 3	1 7
R-3, Pu/Th	A	969	439	4 0	37 1	53 7	361 8	22 0	1 7
	B	969	439	4 0	37 5	54 4	531 8	22 0	1 7
	C	969	439	4 0	37 8	54 8	531 9	22 0	1 7
R-4, HEU/Th	A	754	334	3 9	35 5	51 5	281 7	16 7	1 6
	B	754	334	3 9	36 0	52 1	414 0	16 7	1 7
	C	754	334	3 9	36 3	52 6	414 1	16 7	1 7
R-5, ^{233}HEU/Th	A	722	311	3 8	34 8	50 5	267 8	15 6	1 6
	B	722	311	3 8	35 2	51 1	393 6	15 6	1 6
	C	722	311	3 8	35 5	51 5	393 7	15 6	1 6

[a] PF = Partitioned, Full-Decontamination, CL = Coprocessed, Low-Decontamination

[b] A = Government Financing, B = Typical Industrial Financing, C = High-Risk Industrial Financing

Table 6. Summary of Estimated and Derived Costs for Fabrication and Refabrication of LWR and SSCR Fuels

Fuel Cycle	Process[a]	Economic Set[b]	Estimated Costs ($$10^6$)				Derived Costs ($$10^6$)			
			Facility Cost (C_F)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
LEU $(^{235}U,U)O_2$	Fabrication (C)	A	32.0	34.2	23.0	14.1	20.4	20.7	1.7	0.6
		B	32.0	34.2	23.0	14.5	21.0	30.6	1.7	0.7
		C	32.0	34.2	23.0	14.8	21.4	30.7	1.7	0.7
$(^{233}U,U)O_2$	Refabrication (RO/RM)	A	470.5	249.2	27.2	25.4	36.8	186.9	12.5	1.2
		B	470.5	249.2	27.2	26.0	37.7	274.8	12.5	1.2
		C	470.5	249.2	27.2	26.4	38.2	275.0	12.5	1.2
$(^{235}U,Th)O_2$	Fabrication (C)	A	34.8	46.5	24.5	14.6	21.1	24.7	2.3	0.7
		B	34.8	46.5	24.5	15.0	21.8	36.4	2.3	0.7
		C	34.8	46.5	24.5	15.3	22.2	36.5	2.3	0.7
$(^{233}U,Th)O_2$	Refabrication (RO/RM)	A	509.8	265.7	27.4	25.9	37.6	201.0	13.3	1.2
		B	509.8	265.7	27.4	26.5	38.4	295.5	13.3	1.2
		C	509.8	265.7	27.4	26.9	39.0	295.7	13.3	1.2
$(Pu,U)O_2$	Refabrication (RO/CM)	A	208.4	208.5	27.6	24.9	36.2	111.4	10.4	1.2
		B	208.4	208.5	27.6	25.5	37.0	163.8	10.4	1.2
		C	208.4	208.5	27.6	25.9	37.6	164.0	10.4	1.2
$(Pu,U)O_2$	Refabrication (RO/RM)	A	512.7	264.7	27.8	25.8	37.4	201.4	13.2	1.2
		B	512.7	264.7	27.8	26.4	38.3	296.1	13.2	1.2
		C	512.7	264.7	27.8	26.8	38.9	296.3	13.2	1.2
$(Pu,Th)O_2$	Refabrication (RO/CM)	A	224.8	211.3	28.2	25.1	36.3	116.2	10.6	1.2
		B	224.8	211.3	28.2	25.6	37.2	170.9	10.6	1.2
		C	224.8	211.3	28.2	26.0	37.7	171.0	10.6	1.2
$(Pu,Th)O_2$	Refabrication (RO/RM)	A	519.4	265.7	28.6	25.9	37.6	203.3	13.3	1.2
		B	519.4	265.7	28.6	26.5	38.5	299.0	13.3	1.2
		C	519.4	265.7	28.6	26.9	39.0	299.2	13.3	1.2

[a] C = Contact Operation; RO/CM = Remote Operation/Contact Maintenance; RO/RM = Remote Operation/Remote Maintenance.

[b] A = Government Financing; B = Typical Industrial Financing; C = High-Risk Industrial Financing.

Table 7. Summary of Estimated and Derived Costs for Fabrication and Refabrication of HWR Fuels

Fuel Cycle	Process[a]	Economic Set[b]	Estimated Costs ($$10^6$)				Derived Costs ($$10^6$)			
			Facility Cost (C_F)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
UO_2 (Natural)	Fabrication (C)	A	17.9	27.4	10.8	9.8	14.3	14.3	1.4	0.5
		B	17.9	27.4	10.8	10.1	14.6	21.0	1.4	0.5
		C	17.9	27.4	10.8	10.2	14.8	21.1	1.4	0.5
$(^{235}U,U)O_2$	Fabrication (C)	A	21.3	33.2	11.2	11.4	16.5	17.0	1.7	0.5
		B	21.3	33.2	11.2	11.6	16.9	25.1	1.7	0.5
		C	21.3	33.2	11.2	11.8	17.1	25.1	1.7	0.5
$(^{233}U,U)O_2$	Refabrication (RO/RM)	A	414.5	227.0	16.3	18.4	26.7	165.3	11.4	0.8
		B	414.5	227.0	16.3	18.8	27.2	243.0	11.4	0.8
		C	414.5	227.0	16.3	19.0	27.6	243.2	11.4	0.9
$(^{235}U,Th)O_2$	Fabrication (C)	A	22.6	44.2	11.4	11.8	17.1	20.2	2.2	0.5
		B	22.6	44.2	11.4	12.1	17.5	29.8	2.2	0.6
		C	22.6	44.2	11.4	12.2	17.8	29.8	2.2	0.6
$(^{233}U,Th)O_2$	Refabrication (RO/RM)	A	453.9	247.3	17.7	18.5	26.8	180.2	12.4	0.9
		B	453.9	247.3	17.7	18.9	27.4	264.9	12.4	0.9
		C	453.9	247.3	17.7	19.2	27.8	265.0	12.4	0.9
$(Pu,U)O_2$	Refabrication (RO/CM)	A	194.5	195.3	16.7	18.0	26.1	102.5	9.8	0.8
		B	194.5	195.3	16.7	18.4	26.7	148.3	9.8	0.8
		C	194.5	195.3	16.7	18.6	27.0	148.3	9.8	0.9
$(Pu,U)O_2$	Refabrication (RO/RM)	A	454.1	246.3	16.8	18.4	26.7	180.0	12.3	0.9
		B	454.1	246.3	16.8	18.8	27.3	264.6	12.3	0.9
		C	454.1	246.3	16.8	19.1	27.7	264.7	12.3	0.9
$(Pu,Th)O_2$	Refabrication (RO/CM)	A	207.0	196.3	18.1	18.1	26.2	105.9	9.8	0.8
		B	207.0	196.3	18.1	18.5	26.8	155.7	9.8	0.9
		C	207.0	196.3	18.1	18.7	27.2	155.8	9.8	0.9
$(Pu,Th)O_2$	Refabrication (RO/RM)	A	463.5	246.3	18.5	18.5	26.9	182.4	12.3	0.9
		B	463.5	246.3	18.5	18.9	27.5	268.1	12.3	0.9
		C	463.5	246.3	18.5	19.2	27.8	268.2	12.3	0.9

[a] C = Contact Operation; RO/CM = Remote Operation/Contact Maintenance; RO/RM = Remote Operation, Remote Maintenance.

[b] A = Government Financing; B = Typical Industrial Financing; C = High-Risk Industrial Financing.

Table 8. Summary of Estimated and Derived Costs for Fabrication and Refabrication of LMFBR Fuels (Core)

Fuel Cycle	Process[a]	Economic Set[b]	Estimated Costs ($$10^6$)				Derived Costs ($$10^6$)			
			Facility Cost (C_F)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
$(^{235}U,Th)O_2/ThO_2$	Fabrication (C)	A	50.3	81.5	81.8	17.5	25.4	38.1	4.1	0.8
		B	50.3	81.5	81.8	18.6	27.0	56.3	4.1	0.9
		C	50.3	81.5	81.8	19.4	28.1	56.7	4.1	0.9
$(^{233}U,Th)O_2/ThO_2$	Refabrication (RO/RM)	A	1000.8	291.5	82.7	28.4	41.2	330.4	14.6	1.3
		B	1000.8	291.5	82.7	29.7	43.0	486.0	14.6	1.4
		C	1000.8	291.5	82.7	30.5	44.2	486.4	14.6	1.4
$(Pu,U)O_2/UO_2$	Refabrication (RO/CM)	A	357.5	231.9	76.8	27.0	39.2	154.9	11.6	1.2
		B	357.5	231.9	76.8	28.2	40.9	228.1	11.6	1.3
		C	357.5	231.9	76.8	28.9	42.0	228.4	11.6	1.3
$(Pu,U)O_2/UO_2$	Refabrication (RO/RM)	A	938.3	274.4	76.8	28.5	41.4	310.6	13.7	1.3
		B	938.3	274.4	76.8	29.7	43.0	456.9	13.7	1.4
		C	938.3	274.4	76.8	30.5	44.2	457.2	13.7	1.4
$(Pu,Th)O_2/ThO_2$	Refabrication (RO/CM)	A	357.5	231.9	82.7	27.7	40.1	155.1	11.6	1.3
		B	357.5	231.9	82.7	28.9	41.9	228.4	11.6	1.3
		C	357.5	231.9	82.7	29.7	43.1	228.8	11.6	1.4
$(Pu,Th)O_2/ThO_2$	Refabrication (RO/RM)	A	1019.5	309.7	82.7	29.0	42.0	339.8	15.5	1.3
		B	1019.5	309.7	82.7	30.2	43.8	499.8	15.5	1.4
		C	1019.5	309.7	82.7	31.1	45.0	500.1	15.5	1.4
(Pu,U)C/UC	Refabrication (RO/CM)	A	361.6	245.2	63.2	27.1	39.4	159.3	12.3	1.3
		B	361.6	245.2	63.2	28.1	40.8	234.5	12.3	1.3
		C	361.6	245.2	63.2	28.8	41.8	234.8	12.3	1.3
(Pu,U)C/UC	Refabrication (RO/RM)	A	915.5	290.2	63.2	28.5	41.3	308.9	14.5	1.3
		B	915.5	290.2	63.2	29.5	42.8	454.2	14.5	1.4
		C	915.5	290.2	63.2	30.2	43.8	454.5	14.5	1.4
$(^{233}U,Th)C/ThC$	Refabrication (RO/RM)	A	948.7	294.4	70.4	29.0	42.0	318.3	14.7	1.3
		B	948.7	294.4	70.4	30.1	43.6	468.2	14.7	1.4
		C	948.7	294.4	70.4	30.8	44.6	468.5	14.7	1.4
(Pu,Th)C/ThC	Refabrication (RO/CM)	A	368.4	248.9	70.4	27.6	40.0	162.1	12.4	1.3
		B	368.4	248.9	70.4	28.7	41.6	238.6	12.4	1.3
		C	368.4	248.9	70.4	29.4	42.6	238.9	12.4	1.4

Table 8. (Continued)

			Estimated Costs (10^6)				Derived Costs (10^6)			
Fuel Cycle	Process[a]	Economic Set[b]	Facility Cost (C_F)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
(Pu,Th)C/ThC	Refabrication (RO/RM)	A	948.7	294.9	70.4	29.0	42.0	318.4	14.7	1.3
		B	948.7	294.9	70.4	30.1	43.6	468.4	14.7	1.4
		C	948.7	294.9	70.4	30.8	44.7	468.7	14.7	1.4
Pu,U,Zr/U	Refabrication (RO/CM)	A	339.6	202.8	71.3	28.9	41.9	143.8	10.1	1.3
		B	339.6	202.8	71.3	30.0	43.5	211.7	10.1	1.4
		C	339.6	202.8	71.3	30.7	44.6	212.0	10.1	1.4
Pu,U,Zr/U	Refabrication (RO/RM)	A	841.5	235.7	71.3	30.3	43.9	277.4	11.8	1.4
		B	841.5	235.7	71.3	31.4	45.5	408.1	11.8	1.5
		C	841.5	235.7	71.3	32.2	46.6	408.4	11.8	1.5
^{233}U,Th/Th	Refabrication (RO/RM)	A	934.5	259.7	71.1	30.6	44.4	306.7	13.0	1.4
		B	934.5	259.7	71.1	31.8	46.0	451.0	13.0	1.5
		C	934.5	259.7	71.1	32.5	47.1	451.4	13.0	1.5
Pu,Th/Th	Refabrication (RO/CM)	A	379.2	219.6	71.1	29.5	42.8	158.1	11.0	1.4
		B	379.2	219.6	71.1	30.6	44.4	232.6	11.0	1.4
		C	379.2	219.6	71.1	31.4	45.5	233.0	11.0	1.4
Pu,Th/Th	Refabrication (RO/RM)	A	934.5	259.7	71.1	30.6	44.4	306.6	13.0	1.4
		B	934.5	259.7	71.1	31.8	46.0	446.7	13.0	1.5
		C	934.5	259.7	71.1	32.5	47.1	446.9	13.0	1.5

[a] C = Contact Operation; RO/CM = Remote Operation/Contact Maintenance; RO/RM = Remote Operation/Remote Maintenance.

[b] A = Government Financing; B = Typical Industrial Financing; C = High-Risk Industrial Financing.

Table 9. Summary of Estimated and Derived Costs for Fabrication and Refabrication of LMFBR Fuels (Radial Blanket)

Fuel Cycle	Process[a]	Economic Set[b]	Estimated Costs ($10^6): Facility Cost ($C_F$)	Estimated Costs ($10^6): Equipment Cost ($C_E$)	Estimated Costs ($10^6): Annual Hardware and Material Cost (M)	Estimated Costs ($10^6): Annual Operating Cost (O)	Derived Costs ($10^6): Owner's Cost During Construction (C_O)	Derived Costs ($10^6): Charge on Direct Capital During Construction (C_C)	Derived Costs ($10^6): Annual Equipment Replacement Cost (E_R)	Derived Costs ($10^6): Annual Payment to Decommissioning Fund (D)
UO_2	Fabrication (C)	A	24.3	33.6	33.1	14.3	20.7	18.7	1.7	0.7
		B	24.3	33.6	33.1	14.8	21.4	27.7	1.7	0.7
		C	24.3	33.6	33.1	15.1	21.9	27.8	1.7	0.7
ThO_2	Fabrication (C)	A	25.9	36.9	36.3	14.3	20.8	20.0	1.8	0.7
		B	25.9	36.9	36.3	14.9	21.6	29.5	1.8	0.7
		C	25.9	36.9	36.3	15.2	22.1	29.7	1.8	0.7
ThO_2	Refabrication (RO/RM)	A	478.3	333.8	33.5	27.5	39.9	210.5	16.7	1.3
		B	478.3	333.8	33.5	28.2	40.9	309.6	16.7	1.3
		C	478.3	333.8	33.5	28.6	41.5	309.8	16.7	1.3
UC	Fabrication (C)	A	35.3	56.5	30.6	14.2	20.6	27.2	2.8	0.7
		B	35.3	56.5	30.6	14.7	21.3	40.1	2.8	0.7
		C	35.3	56.5	30.6	15.0	21.8	40.2	2.8	0.7
ThC	Fabrication (C)	A	36.5	61.1	38.0	14.3	20.8	28.6	3.1	0.7
		B	36.5	61.1	38.0	14.8	21.6	42.3	3.1	0.7
		C	36.5	61.1	38.0	15.3	22.2	42.4	3.1	0.7
ThC	Refabrication (RO/RM)	A	783.0	251.7	35.1	28.3	41.0	266.2	12.6	1.3
		B	783.0	251.7	35.1	29.0	42.1	391.4	12.6	1.3
		C	783.0	251.7	35.1	29.5	42.7	391.6	12.6	1.4
U	Fabrication (C)	A	33.9	31.7	28.2	14.2	20.5	20.6	1.6	0.7
		B	33.9	31.7	28.2	14.6	21.2	30.4	1.6	0.7
		C	33.9	31.7	28.2	14.9	21.7	30.6	1.6	0.7
Th	Fabrication (C)	A	38.2	37.8	38.1	14.3	20.8	23.3	1.9	0.7
		B	38.2	37.8	38.1	14.9	21.6	34.4	1.9	0.7
		C	38.2	37.8	38.1	15.3	22.2	34.5	1.9	0.7
Th	Refabrication (RO/RM)	A	763.3	212.7	35.2	30.0	43.4	252.1	10.6	1.4
		B	763.3	212.7	35.2	30.7	44.5	370.7	10.6	1.4
		C	763.3	212.7	35.2	31.2	45.2	370.9	10.6	1.4

[a] C = Contact Operation; RO/RM = Remote Operation, Remote Maintenance.

[b] A = Government Financing; B = Typical Industrial Financing; C = High-Risk Industrial Financing.

Table 10. Summary of Estimated and Derived Costs for Fabrication and Refabrication of HTGR Fuels

Fuel Cycle	Process	Economic Set[a]	Estimated Costs ($10^6)				Derived Costs ($10^6)			
			Facility Cost (C_F)	Equipment Cost (C_E)	Annual Hardware and Material Cost (M)	Annual Operating Cost (O)	Owner's Cost During Construction (C_O)	Charge on Direct Capital During Construction (C_C)	Annual Equipment Replacement Cost (E_R)	Annual Payment to Decommissioning Fund (D)
OT-1, LEU Stowaway	Fabrication	A	87.0	266.0	184.0	26.9	39.0	96.0	13.3	1.2
		B	87.0	266.0	184.0	29.2	42.4	142.0	13.3	1.3
		C	87.0	266.0	184.0	30.8	44.6	142.7	13.3	1.4
OT-2, MEU/Th Stowaway, Current	Fabrication	A	81.0	260.0	168.0	23.5	34.1	92.0	13.0	1.1
		B	81.0	260.0	168.0	25.6	37.2	136.1	13.0	1.2
		C	81.0	260.0	168.0	27.0	39.2	136.7	13.0	1.2
OT-3, MEU/Th Stowaway, Optimized	Fabrication	A	76.0	244.0	157.0	22.3	32.3	86.4	12.2	1.0
		B	76.0	244.0	157.0	24.3	35.2	127.8	12.2	1.1
		C	76.0	244.0	157.0	25.6	37.1	128.4	12.2	1.2
R-1, ^{235}MEU/Th	Fabrication	A	71.0	227.0	146.0	22.1	32.0	80.9	11.4	1.0
		B	71.0	227.0	146.0	23.9	34.7	119.6	11.4	1.1
		C	71.0	227.0	146.0	25.2	36.5	120.1	11.4	1.2
R-1, ^{235}MEU/Th	Refabrication	A	395.0	809.0	113.0	42.9	62.2	312.8	40.4	2.0
		B	395.0	809.0	113.0	44.6	64.7	460.3	40.4	2.1
		C	395.0	809.0	113.0	45.7	66.3	460.8	40.4	2.1
R-2, ^{233}MEU/Th	Refabrication	A	320.0	807.0	88.0	42.4	61.5	293.5	40.3	2.0
		B	320.0	807.0	88.0	43.8	63.6	431.7	40.3	2.0
		C	320.0	807.0	88.0	44.8	65.0	432.2	40.3	2.1
R-3, Pu/Th	Refabrication	A	569.0	807.0	172.0	39.9	57.9	354.7	40.3	1.8
		B	569.0	807.0	172.0	42.2	61.2	522.2	40.3	2.0
		C	569.0	807.0	172.0	43.8	63.5	522.9	40.3	2.0
R-4, HEU/Th	Fabrication	A	51.0	166.0	94.0	15.0	21.8	58.6	8.3	0.7
		B	51.0	166.0	94.0	16.2	23.5	86.5	8.3	0.7
		C	51.0	166.0	94.0	17.0	24.7	86.9	8.3	0.8
R-4, HEU/Th	Refabrication	A	304.0	498.0	89.0	26.1	37.9	207.6	24.9	1.2
		B	304.0	498.0	89.0	27.4	39.7	305.6	24.9	1.3
		C	304.0	498.0	89.0	28.2	40.9	305.9	24.9	1.3
R-5, ^{233}HEU/Th	Refabrication	A	265.0	450.0	78.4	24.9	36.1	185.6	22.5	1.2
		B	265.0	450.0	78.4	26.0	37.8	273.1	22.5	1.2
		C	265.0	450.0	78.4	26.8	38.9	273.5	22.5	1.2

[a] A = Government Financing; B = Typical Industrial Financing; C = High-Risk Industrial Financing.

Table 11. Reference Fuel Reprocessing Plant Unit Cost Estimates[a]

Reactor	Process Case[b]	Unit Costs, $/kg Heavy Metal			
		Government	Typical Industry	High-Risk Industry	Approximate Electric Power Support (GWe)
LWR/SSCR	$(Pu,U)O_2$/PF	120	230	310	58.1
	$(Pu,U)O_2$/CL	110	220	300	58.1
	$(U,Th)O_2$/PF	120	240	320	65.0
	$(U,Th)O_2$/CL	120	230	310	65.0
HWR	$(Pu,U)O_2$/PF	120	230	310	27.8
	$(Pu,U)O_2$/CL	120	220	300	27.8
	$(U,Th)O_2$/PF	120	240	320	27.8
	$(U,Th)O_2$/CL	120	230	310	27.8
LMFBR-Oxide	$(Pu,U)O_2$;UO_2/PF	120	230	310	51.9
	$(Pu,U)O_2$;UO_2/CL	120	230	300	51.9
	$(U,Th)O_2$;ThO_2/PF	120	240	320	54.1
	$(U,Th)O_2$;ThO_2/CL	120	230	310	54.1
LMFBR-Carbide	(Pu,U)C;UC/PF	140	260	350	66.9
	(Pu,U)C;UC/CL	130	260	340	66.9
	(U,Th)C;ThC/PF	140	270	360	81.3
	(U,Th)C;ThC/CL	130	260	350	81.3
LMFBR-Metal	Pu,U,Zr;U/PF	120	240	320	50.0
	Pu,U,Zr;U/CL	120	230	310	50.0
	U,Th;Th/PF	130	240	330	60.3
	U,Th;Th/CL	120	240	320	60.3
HTGR	R-1, ^{235}MEU/Th	160	320	430	176.6
	R-2, ^{233}MEU/Th	150	280	380	101.9
	R-3, Pu/Th	170	340	460	208.8
	R-4, ^{235}HEU/Th	140	270	370	127.2
	R-5, ^{233}HEU/Th	130	260	350	75.0

[a]Plant capacity: 5 MT/d = 1500 MT/year. Reprocessing of combined core plus axial blanket materials.

[b]PF = Partitioned, Full Decontamination; CL = Coprocessed, Low Decontamination.

Table 12. Reference LWR and SSCR Fuel Fabrication Plant Unit Cost Estimates[a]

Fuel Type	Plant Type[b]	Unit Costs,[c] $/kg HM			Production Rate (Fuel Elements Per Year)	Approximate Electric Power Support (GWe)
		Government	Typical Industry	High-Risk Industry		
LEU $(^{235}U,U)O_2$	C	100	130	150	1130	20.2
$(^{233}U,U)O_2$	RO/RM	350	630	820	1040	18.7
$(^{235}U,Th)O_2$	C	110	140	170	1200	21.6
$(^{233}U,Th)O_2$	RO/RM	370	660	870	1240	20.8
$(Pu,U)O_2$	RO/CM	260	430	540	1040	18.6
$(Pu,U)O_2$	RO/RM	370	670	880	1040	18.6
$(Pu,Th)O_2$	RO/CM	270	440	560	1240	20.8
$(Pu,Th)O_2$	RO/RM	370	670	890	1240	20.8

[a]Plant capacities: 2 MT/d = 520 MT/year contact or 480 MT/year remote. Fuel element design data derived from NASAP-supplied information. T. M. Helm et al. (comps. and eds.), *Reactor Design Characteristics and Fuel Inventory Data,* limited-distribution report compiled by Hanford Engineering Development Laboratory (September 1977).

[b]Plant types: C = contact; RO/CM = remotely operated, contact maintained; RO/RM = remotely operated, remotely maintained.

[c]Does *not* include cost of ThO_2, UO_2, or PuO_2.

on the fuel element design descriptions given in Appendix A. Because of the uncertainties associated with the specific designs to be used, as well as other uncertainties in the estimates, it is important to recognize that small differences in unit costs should not be the basis for choice of fuel or fuel cycle. The differences given are those associated with a consistent evaluation using the specified ground rules.

The reference plants that were considered in this study were assumed to operate as toll processing facilities. In this type of operation, fuel feed materials are provided by customers and the feed materials are converted to the finished products by the facility operators. Thus, the costs of uranium, plutonium, and thorium are not included in the unit cost determinations. In all cases, unit costs were

Table 13. Reference HWR Fuel Fabrication Plant Unit Cost Estimates[a]

Fuel Type	Plant Type[b]	Unit Costs,[c] $/kg HM			Production Rate (Fuel Elements Per Year)	Approximate Electric Power Support (GWe)
		Government	Typical Industry	High-Risk Industry		
UO_2 (Natural)	C	60	80	95	27,800	4.5
$(^{235}U,U)O_2$	C	65	90	110	27,800	9.7
$(^{233}U,U)O_2$	RO/RM	290	530	700	25,670	8.9
$(^{235}U,Th)O_2$	C	75	100	120	31,900	9.7
$(^{233}U,Th)O_2$	RO/RM	310	570	760	29,450	8.9
$(Pu,U)O_2$	RO/CM	210	360	470	25,670	8.9
$(Pu,U)O_2$	RO/RM	310	570	760	25,670	8.9
$(Pu,Th)O_2$	RO/CM	220	370	480	29,450	8.9
$(Pu,Th)O_2$	RO/RM	310	580	770	29,450	8.9

[a]Plant capacities: 2 MT/d = 520/year contact or 480 MT/year remote. Fuel element design data derived from NASAP-supplied information. T. M. Helm et al. (comps. and eds.), *Reactor Design Characteristics and Fuel Inventory Data,* limited-distribution report compiled by Hanford Engineering Development Laboratory (September 1977).

[b]Plant Types: C = contact; RO/CM = remotely operated, contact maintained; RO/RM = remotely operated, remotely maintained.

[c]Does *not* include cost of ThO_2, UO_2, or PuO_2.

based on established industries; therefore, first-of-a-kind costs and research and development costs needed to establish the industries were not included in unit cost determinations.

PROVISIONAL DATA BASE COST ESTIMATES INPUT

Unit costs as a function of time (i.e., reactor industry growth) are required for the NASAP evaluation of the various fuel cycles. Thus, the input to the NASAP provisional data base must include consideration of changes of fuel plant capacities with an assumed reactor industry growth rate.

Table 14. Reference Fuel Fabrication Plant Unit Cost Estimates,[a] FBR Core Assemblies

Fuel Type Core/Axial Blanket	Plant Type[b]	Unit Costs,[c] $/kg HM			Production Rate (Fuel Elements Per Year)	Approximate Electric Power Support (GWe)
		Government	Typical Industry	High-Risk Industry		
$(^{235}U,Th)O_2/ThO_2$	C	240	300	340	4030	18.9
$(^{233}U,Th)O_2/ThO_2$	RO/RM	640	1120	1470	3720	17.3
$(Pu,U)O_2/UO_2$	RO/CM	420	650	810	3420	16.6
$(Pu,U)O_2/UO_2$	RO/RM	600	1060	1380	3420	16.6
$(Pu,Th)O_2/ThO_2$	RO/CM	430	660	830	3720	18.1
$(Pu,Th)O_2/ThO_2$	RO/RM	650	1150	1510	3720	18.1
(Pu,U)C/UC	RO/CM	400	630	800	2760	21.4
(Pu,U)C/UC	RO/RM	570	1030	1350	2760	21.4
$(^{233}U,Th)C/ThC$	RO/RM	600	1070	1400	3350	26.0
(Pu,Th)C/ThC	RO/CM	420	660	830	3350	26.0
(Pu,Th)C/ThC	RO/RM	600	1070	1400	3350	26.0
Pu,U,Zr/U	RO/CM	400	610	760	2420	16.0
Pu,U,Zr/U	RO/RM	550	960	1250	2420	16.0
Pu,Th/Th	RO/CM	420	650	820	2910	19.3
Pu,Th/Th	RO/RM	590	1040	1360	2910	19.3
$^{233}U,Th/Th$	RO/RM	590	1040	1360	2910	19.3

[a]Plant capacities: 2 MTHM/d = 520 MTHM/year contact or 480 MTHM/year remote. Fuel element design data derived from ANL-NASAP-supplied information. Y. A. Chang, Argonne National Laboratory, personal communication to J. M. Cleveland, Oak Ridge National Laboratory (April—May 1978).

[b]Plant types: C = contact; RO/CM = remotely operated, contact maintained; RO/RM = remotely operated, remotely maintained.

[c]Does *not* include cost of uranium, thorium, or plutonium materials. HM = total heavy metal in assembly, including core and axial blanket.

Table 15. Reference Fuel Fabrication Plant Unit Cost Estimates,[a] FBR Radial Blankets

Fuel Type	Plant Type[b]	Unit Costs,[c] $/kg HM			Production Rate (Fuel Elements Per Year)
		Government	Typical Industry	High-Risk Industry	
UO_2	C	120	140	160	2710
ThO_2	C	120	150	170	2970
ThO_2	RO/RM	400	710	930	2750
UC	C	120	160	190	2000
ThC	C	140	180	210	2560
ThC	RO/RM	460	850	1130	2360
U	C	110	140	160	1520
Th	C	130	160	190	2330
Th	RO/RM	450	820	1080	2150

[a] Plant capacities: 2 MT/d = 520 MT/year contact or 480 MT/year remote. Element design data derived from INFCE-supplied information. W. O. Harms, Oak Ridge National Laboratory, personal communication to P. R. Kasten, Oak Ridge National Laboratory (May 19, 1978).

[b] Plant types: C = contact; RO/RM = remotely operated, remotely maintained.

[c] Does *not* include cost of thorium or uranium materials.

Inclusion of first-of-a-kind plant costs in the data base could unreasonably distort the fuel cycle evaluations. Thus, the unit costs presented in Tables 11 through 16 were based on established, or mature, industries, and these unit costs were used to derive the input to the data base. In order to convert the reference plant costs to the required data base format, scaling factors were established for conversion of the reference plant costs to other capacities. The lower capacity plants were based on early commercial application and the higher

Table 16. Reference HTGR Fuel Fabrication Plant Unit Cost Estimates[a]

Fuel Type	Plant Type[b]	Unit Costs,[c] $/kg HM			Production Rate (Fuel Elements Per Year)	Approximate Electric Power Support (GWe)
		Government	Typical Industry	High-Risk Industry		
OT-1, LEU Stowaway	C	530	670	770	106,560	80.5
OT-2, MEU/Th Stowaway (Current)	C	490	620	720	93,110	93.8
OT-3, MEU/Th Stowaway (Optimized)	C	460	580	670	84,990	85.6
R-1, ^{235}MEU/Th	C	430	550	630	74,820	75.4
R-1, ^{235}MEU/Th	RO/RM	770	1230	1560	56,080	56.5
R-2, ^{233}MEU/Th	RO/RM	690	1130	1430	43,130	32.6
R-3, Pu/Th	RO/RM	930	1460	1830	88,400	66.8
R-4, HEU/Th	C	290	370	430	43,410	43.7
R-4, HEU/Th	RO/RM	530	840	1060	40,370	40.7
R-5, ^{233}HEU/Th	RO/RM	480	750	940	34,040	24.0

[a]Plant capacities: 2 MT/d = 520 MT/year contact or 480 MT/year remote. Fuel element design data derived from GA-NASAP-supplied information. A. J. Neylan, General Atomic Company, personal communication to K. O. Laughon, Department of Energy (March 3, 1978); R. K. Lane, General Atomic Company, personal communication to A. R. Olsen, Oak Ridge National Laboratory (July 17, 1978).

[b]Plant types: C = contact; RO/RM = remotely operated, remotely maintained.

[c]Does *not* include cost of $Th(NO_3)_4$, UO_2, or PuO_2.

capacity plants were based on fuel requirements for a large reactor industry. Scaling factors that were used were based on an analysis of similar industries for which scaling factors were reasonably well established[6] and on cost estimates of plants that differed only in capacity.

A standard equation for estimating costs as a function of capacity is

$$C_u = C_o(X_u/X_o)^Y ,$$

where

C_u = cost of unknown plant in a given category,

C_o = cost of reference plant in a given category,

X_u = capacity of unknown plant,

X_o = capacity of reference plant,

Y = scaling factor for the cost category.

The scaling factors used for this study are

$Y = 0.35$ for all categories in the reprocessing plant;

$Y = 0.6$ for contact fabrication facility costs;

$Y = 0.8$ for remotely operated fabrication facility costs;

$Y = 0.7$ for equipment in fabrication plants;

$Y = 1.0$ for expendable materials and hardware in fabrication plants;

$Y = 0.8$ for operating costs in fabrication plants.

Scaling factors are, of course, affected by a number of variables, such as criticality considerations, plant throughput, reliability of equipment, and differences in facilities due to materials being processed. Scaling factors may vary widely with equipment type and application and generally are not used beyond a tenfold range of capacity. The scaling factors presented above represent what are believed to be reasonable values of the average scaling factors for the reprocessing and refabrication plants over the fourfold range of capacities considered in this study. These scaling factors were applied to the reference plant costs. Unit costs for different sized plants were calculated from the scaled plant costs by use of the unit price analysis formula.

The capacities of plants for which cost estimates were obtained for the provisional data base were based on an assessment of the electrical industry size that could be supported by the lower capacity plants. Consideration was given to geographical dispersement of reactors, capital investment, competition, and technology obsolescence to establish a practical upper limit to the high-capacity plants. In selecting plant capacities, the attempt was to assure that the plants were sufficiently large to be commercially competitive and would meet the fuel requirements of the reactor industry. The selected capacities are given, together with the resulting unit costs, in Table 17 for reprocessing and in Table 18 for fabrication and refabrication. The unit costs presented are based on typical industrial financing and are the recommended unit

Table 17. Reprocessing Costs for Reference Purex and Thorex Cases as a Function of Plant Capacity[a]

Reactor	Fuel Type	Developed Industry		High-Capacity Industry	
		Unit Cost ($/kg HM)	Plant Capacity (MTHM/d)	Unit Cost ($/kg HM)	Plant Capacity (MTHM/d)
LWR,SSCR	$(Pu,U)O_2$	230	5	150	10
	$(U,Th)O_2$	240	5	150	10
HWR	$(Pu,U)O_2$	230	5	150	10
	$(U,Th)O_2$	240	5	150	10
LMFBR	$(Pu,U)O_2$	230	5	150	10
	$(U,Th)O_2$	240	5	150	10
	(Pu,U)C	260	5	170	10
	(U,Th)C	270	5	170	10
	(U,Pu,Zr)metal	240	5	150	10
	(U,Th)metal	240	5	160	10
HTGR	R-1 ^{235}MEU,Th	570	2	320	5
	R-2 ^{233}MEU,Th	510	2	280	5
	R-3 Pu,Th	620	2	340	5
	R-4 HEU,Th	490	2	270	5
	R-5 ^{233}HEU,Th	470	2	260	5

[a]The first (developed industry) cost is for the year of introduction and does not include first-of-a-kind costs; a time span of 15 years is estimated from introduction pricing until high-capacity industry pricing prevails. Cost uncertainties: ±25%. January 1978 dollars.

costs for the provisional data base to be used in the next fuel cycle analysis for NASAP. All costs in Tables 17 and 18 have been rounded to the nearest $10, except those less than $100/kg HM were rounded to the nearest $5.

Table 18. Fabrication Costs as a Function of Plant Capacity[a]

Reactor	Fuel Type	Developed Industry Unit Cost ($/kg)	Developed Industry Plant Capacity (MTHM/d)	High-Capacity Industry Unit Cost ($/kg)	High-Capacity Industry Plant Capacity (MTHM/d)
PWR,SSCR	LEU($^{235}U,U)O_2$	110	6	110	6
	$(^{235}U,Th)O_2$	140	2	120	4
	$(^{233}U,U)O_2$	630	2	540	4
	$(^{233}U,Th)O_2$	660	2	570	4
	$(Pu,U)O_2$ (RO/CM)	430	2	370	4
	$(Pu,Th)O_2$ (RO/CM)	440	2	380	4
	$(Pu,U)O_2$ (RO/RM)	670	2	580	4
	$(PU,Th)O_2$ (RO/RM)	670	2	580	4
HWR	UO_2 (Natural)	65	6	65	6
	$(^{235}U,U)O_2$	75	6	75	6
	$(^{235}U,Th)O_2$	100	2	80	6
	$(^{233}U,U)O_2$	530	2	450	4
	$(^{233}U,Th)O_2$	570	2	490	4
	$(Pu,U)O_2$ (RO/CM)	360	2	310	4
	$(Pu,Th)O_2$ (RO/CM)	370	2	320	4
	$(Pu,U)O_2$ (RO/RM)	570	2	490	4
	$(Pu,Th)O_2$ (RO/RM)	580	2	500	4
FBR Oxide[b]	$(^{235}U,Th)O_2/ThO_2$	300	2	260	4
	$(^{233}U,Th)O_2/ThO_2$	1120	2	990	4
	$(Pu,U)O_2/UO_2$ (RO/CM)	650	2	580	4
	$(Pu,Th)O_2/ThO_2$ (RO/CM)	660	2	590	4
	$(Pu,U)O_2/UO_2$ (RO/RM)	1060	2	930	4
	$(Pu,Th)O_2/UO_2$ (RO/RM)	1150	2	1010	4
	UO_2 Radial Blanket	140	2	130	4
	ThO_2 Radial Blanket	150	2	140	4
FBR Carbide[b]	$(^{233}U,Th)C/ThC$	1070	2	940	4
	(Pu,U)C/UC (RO/CM)	630	2	560	4
	(Pu,Th)C/ThC (RO/CM)	660	2	580	4
	(Pu,U)C/UC (RO/RM)	1030	2	900	4
	(Pu,Th)C/ThC (RO/RM)	1070	2	940	4
	UC Radial Blanket	160	2	140	4
	ThC Radial Blanket	180	2	160	4
FBR Metal[b]	^{233}U,Th/Th	1040	2	910	4
	Pu,U,Zr/U (RO/CM)	610	2	540	4
	Pu,Th/Th (RO/CM)	650	2	580	4
	Pu,U/U (RO/RM)	960	2	850	4
	Pu,Th/Th (RO/RM)	1040	2	910	4
	U Radial Blanket	140	2	120	4
	Th Radial Blanket	160	2	150	4
HTGR	OT-1, LEU Stowaway (C)	740	1.0	670	2
	OT-2, MEU/Th Stowaway (C)	690	1.0	620	2
	OT-3, MEU/Th Stowaway (C)	640	1.0	580	2
	R-1, ^{235}MEU/Th (C)	610	1.0	550	2
	R-1, ^{235}MEU/Th (RO/RM)	1960	0.5	1230	2
	R-2, ^{233}MEU/Th (RO/RM)	1130	2.0	970	4
	R-3, Pu/Th (RO/RM)	1670	1.0	1460	2
	R-4, HEU/Th (C)	410	1.0	370	2
	R-4, HEU/Th (RO/RM)	960	1.0	840	2
	R-5, ^{233}HEU/Th (RO/RM)	750	2.0	660	4

[a]The first (developed industry) cost is for the year of introduction and does not include first-of-a-kind costs; a time span of 15 years is estimated from introduction pricing until high capacity industry pricing prevails. Cost uncertainty: ^{235}U fuels, ±10%, Pu fuels, ±25%, ^{233}U fuels, ±25%. January 1978 dollars.

[b]Unit cost for core fuel assemblies applies to total heavy metal throughput for core plus axial blanket.

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This assistance, which we gratefully acknowledge, has provided an improved framework for the current estimates. Each of the process functional areas has been examined in greater detail than previously, additional details for process support areas have been considered, and the distribution of costs to specific categories has been modified to comply with most of the suggestions of the reviewers.

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APPENDIX A

DESIGN CHARACTERISTICS FOR FUEL ASSEMBLIES USED IN UNIT COST ESTIMATIONS FOR FABRICATION, REPROCESSING, AND REFABRICATION

Table A1. Design Characteristics of Fuel Used for Cost Estimations Light Water Reactors and Spectral Shift Control Reactors[a]

Characteristics	HEDL Data[b]	C-E Data[b]
Reactor output, MWe (Net)	1150	1300
Fuel assemblies/core	193	241
Fuel assemblies/reload	∿64	∿80
Fuel rod array	17 × 17 square	16 × 16 square
Fuel rods/assembly	264	236
Enrichments/assembly	1	1
Cladding material	Zircaloy-4	Zircaloy-4
Cladding outside diameter, mm (in.)	9.50 (0.374)	9.70 (0.382)
Cladding inside diameter, mm (in.)	8.36 (0.329)	8.43 (0.332)
Pellet diameter, mm (in.)	8.192 (0.3225)	8.26 (0.325)
Pellet length, mm (in.)	13.46 (0.530)	9.91 (0.390)
Pellet stack height, mm (in.)	3650 (143.7)	3810 (150.0)

Fuel	Data Reference	Fissile Content (%)	Density (% TD)	Heavy Metal Content, kg	
				Rod	Assembly
$(^{235}U,U)O_2$	HEDL	3.0	95	1.75	461
$(^{235}U,Th)O_2$	HEDL	4.9	95	1.64	432
$(^{233}U,U)O_2$		3.0[c]	95[c]	1.75[c]	461[c]
$(^{233}U,Th)O_2$	C-E	3.2	95	1.64	388
$(Pu,U)O_2$	HEDL	3.5	95	1.75	461
$(Pu,Th)O_2$	C-E	5.8	95	1.64	388

[a]T. M. Helm, et al. (comps. and eds.), *Reactor Design Characteristics and Fuel Inventory Data*, limited-distribution report compiled by Hanford Engineering Development Laboratory (September 1977).

[b]HEDL — Hanford Engineering Development Laboratory; C-E — Combustion Engineering.

[c]Assumed values; data not available.

Table A2. Design Characteristics of Fuel Used for Cost Estimations, Heavy Water Reactors[a]

Characteristics	ANL Data (A)[b]	ANL Data (B)[b]
Reactor output, MWe (Net)	1000	1000
Fuel assemblies/core	7108	7204
Fuel assemblies/reload	On-line refueling	On-line refueling
Fuel assembly array	Circular	Circular
Fuel rods/assembly	37	37
Enrichments/assembly	1	1
Cladding material	Zircaloy-4	Zircaloy-4
Cladding outside diameter, mm (in.)	13.08 (0.515)	13.08 (0.515)
Cladding inside diameter, mm (in.)	12.24 (0.482)	12.24 (0.482)
Pellet diameter, mm (in.)	12.14 (0.478)	12.14 (0.478)
Pellet length, mm (in.)	8.00 (0.315)	8.00 (0.315)
Pellet stack height, mm (in.)	477 (18.8)	475 (18.7)

Fuel	Data Reference	Fissile Content (%)	Density (% TD)	Heavy Metal Content, kg	
				Rod	Assembly
UO_2 (Natural)	ANL (B)	0.711	94.5	0.51	18.7
$(^{235}U,U)O_2$ (SE)	ANL (B)	1.00	94.5	0.51	18.7
$(^{235}U,Th)O_2$	ANL (A)	1.54	95[c]	0.44	16.3
$(^{233}U,U)O_2$		1.00[c]	94.5[c]	0.51[c]	18.7[c]
$(^{233}U,Th)O_2$	ANL (A)	1.54	95[c]	0.44	16.3
$(Pu,U)O_2$		1.01[c]	95[c]	0.51[c]	18.7[c]
$(Pu,Th)O_2$	ANL (A)	1.73	95[c]	0.44	16.3

[a]T. M. Helm, et al. (comps. and eds.), *Reactor Design Characteristics and Fuel Inventory Data,* limited-distribution report compiled by Hanford Engineering Development Laboratory (September 1977).

[b]ANL — Argonne National Laboratory.

[c]Assumed values; data not available.

Table A3. Design Characteristics of Fuel Used for Cost Estimations, Liquid Metal Fast Breeder Reactors — Core/Axial Blanket ANL NASAP Data[a]

Characteristics	Oxides	Carbides	Metals
Reactor output, MWe	1000[b]	1000[b]	1000[b]
Fuel assemblies/core	357	258	303
Fuel assemblies/reload	178	129	151
Bonding	He	Na	Na
Fuel rods/assembly	271	169	169
Smear density, % TD	88	86	75 (U) 85 (Th)
Cladding material	316SS	316SS	316SS
Cladding outside diameter, mm (in.)	7.37 (0.290)	8.89 (0.350)	8.89 (0.350)
Cladding inside diameter, mm (in.)	6.60 (0.260)	8.13 (0.320)	8.13 (0.320)
Pellet diameter, mm (in.)	6.35 (0.250)	7.75 (0.305)	7.04 (U) (0.277) (U) 7.49 (Th) (0.295) (Th)
Pellet length, mm (in.)	6.35 (0.250)	7.75 (0.305)	7.04 (U) (0.277) (U) 7.49 (Th) (0.295) (Th)
Pellet stack height, total, mm (in.)	1778 (70)	1778 (70)	1778 (70)
core, mm (in.)	1016 (40)	1016 (40)	1016 (40)

Fuel	Density[b] (% TD)	Heavy Metal Content, kg	
		Rod	Assembly
$(^{233}U,Th)O_2/ThO_2$	95	0.48[b]	128.9[b]
$(Pu,U)O_2/UO_2$	95	0.52	140.3
$(Pu,Th)O_2/ThO_2$	95	0.48	128.9
$(^{233}U,Th)C/ThC$	95	0.85[b]	143.1[b]
(Pu,U)C/UC	95	1.03	173.9
(Pu,Th)C/ThC	95	0.85	143.1
$^{233}U,Th/Th$	100	0.98[b]	164.9[b]
Pu,U,Zr/U	100	1.17	198.0
Pu,Th/Th	100	0.98	164.9

[a]ANL — Argonne National Laboratory. Y. A. Chang, Argonne National Laboratory, personal communication to J. M. Cleveland, Oak Ridge National Laboratory (April—May 1978).

[b]Assumed values; data not available.

Table A4. Design Characteristics of Fuel Used for Cost Estimations, Liquid Metal Fast Breeder Reactors — Radial Blanket ANL INFCE Data[a]

Characteristics	Oxides	Carbides	Metals
Reactor output, MWe	1000[b]	1000[b]	1000[b]
Fuel assemblies/core	234	186	204
Fuel assemblies/reload	47	37	41
Bonding	He	Na	Na
Fuel rods/assembly	127	127	127
Smear density, % TD	90	90	85[b]
Cladding material	316SS	316SS	316SS
Cladding outside diameter, mm (in.)	11.94 (0.470)	11.99 (0.472)	11.71 (0.461)
Cladding inside diameter, mm (in.)	11.18 (0.440)	11.23 (0.442)	10.95 (0.431)
Pellet diameter, mm (in.)	10.87 (0.428)	10.92 (0.430)	10.08 (0.397)
Pellet length, mm (in.)	10.87 (0.428)	10.92 (0.430)	10.08 (0.397)
Pellet stack height, mm (in.)	1778 (70)	1778 (70)	1778 (70)

Blanket Material	Density[b]		Heavy Metal Content, kg	
	(% TD)	(Mg/m^3)	Rod	Assembly
UO_2	95	10.41	1.51	192.22
ThO_2	95	9.50	1.38	174.85
UC	95	12.95	2.05	260.42
ThC	95	10.08	1.60	203.14
U	100	19.07	2.70	343.21
Th	100	11.66	1.76	223.24

[a]ANL — Argonne National Laboratory. W. O. Harms, Oak Ridge National Laboratory, personal communication to P. R. Kasten, Oak Ridge National Laboratory (May 19, 1978).

[b]Assumed values; data not available.

Table A5. Design Characteristics of Fuel Used for Cost Estimations High-Temperature Gas-Cooled Reactors (HTGR)[a]

	Standard Elements[b]							
	OT-1	OT-2	OT-3	R-1 (Fab Refab)	R-2	R-3	R-4 (Fab Refab)	R-5
Reactor output, MWe	1332	1332	1332	1332	1332	1332	1332	1332
Fuel assemblies/core	5288	5288	5288	5288	5288	5288	5288	7548
Fuel assemblies/reload	1763	1322	661	1322	1763	1763	1322	1887
Reload frequency, years	1	1	0.5	1	1	1	1	1
Fueled holes/assembly	132	132	132	132	132	132	132	132
Fuel rod diameter, mm	8	11.7	11.1	11.7	15.9	15.9	15.9	15.9
Fuel rods/assembly	1493	1493	1493	1493	1493	1493	1493	1493
Coolant holes/assembly	72	72	72	72	72	72	72	72
Coolant hole diameter, mm	21	21	21	21	21	21	21	21

Cycle Identity	Production Rate[c] (Elements/year)	Fuel	C:HM[d]	Fissile Particle Composition	Fissile Particle Kernel Diameter (μm)	Fertile Particle Composition	Fertile Particle Kernel Diameter (μm)	Heavy Metal Content/Assembly, kg: Fissile Particles	Heavy Metal Content/Assembly, kg: Fertile Particles	Heavy Metal Content/Assembly, kg: Total
OT-1	106,560	LEU ^{235}U-OT	450	UC_2	500	None		4.88		4.88
OT-2	93,110	MEU ^{235}U/Th	385	UC_2	350	ThO_2	500	3.09	2.49	5.58
OT-3	84,970	MEU ^{235}U/Th	348	UC_2	350	ThO_2	500	2.62	3.5	6.12
R-1, Fabrication	74,820	MEU ^{235}U/Th	295	UC_2	350	$(Th/U)O_2$	450	2.84	4.11	6.95
R-1, Refabrication	56,080	MEU ^{233}U/Th	240	UCO	350	$(Th/U)O_2$	450	4.46	4.11	8.57
R-2	43,130	MEU ^{233}U/Th	195	UC_2	350	ThO_2	500	3.99	7.14	11.13
R-3	88,400	Pu/Th	375	$PuO_{1.8}$	200	ThO_2	500	0.84	4.59	5.43
R-4, Fabrication	43,410	HEU ^{235}U/Th	169	UC_2	200	ThO_2	500	0.74	11.24	11.98
R-4, Refabrication	40,370	HEU ^{233}U/Th	170	UCO	360	ThO_2	500	0.65	11.24	11.89
		MEU ^{235}U/Th	162	UCO	360			1.24	11.24	13.01
R-5	34,040	HEU ^{233}U/Th	143	UO_2	360	ThO_2	500	0.56	13.5	14.06

[a]Source is General Atomic data to NASAP, March and July, 1978. A. J. Neylan, General Atomic Company, personal communication to K. O. Laughon, Department of Energy (March 3, 1978); R. K. Lane, General Atomic Company, personal communication to A. R. Olsen, Oak Ridge National Laboratory (July 17, 1978).

[b]Control elements contain fewer fuel holes/assembly and lower heavy metal (HM) contents.

[c]Production rate based on HM output of 2 MT/d at effective full production.

[d]C:HM: Ratio of carbon/assembly to heavy metal/assembly.

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