ATW ECONOMICS

R. A. Krakowski
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

A parametric systems model of the ATW [Accelerator Transmutation of (Nuclear) Waste] has been used to examine key system tradeoffs and design drivers on the basis of unit costs. This model has been applied primarily to the aqueous-slurry blanket concept for an ATW that generates net-electric power from the fissioning of spent reactor fuel. An important goal of this study is the development of essential parametric tradeoff studies to aid in any eventual engineering design of an ATW that would burn and generate net-electric power from spent reactor fuel.

I. INTRODUCTION

Preliminary cost estimates of a net-power-producing ATW [Accelerator Transmutation of (Nuclear) Waste] are reported for a system that would burn low-reactivity LWR [Light-Water (Fission) Reactor] spent fuel. Although the unit costs of electricity production, COE(mill/kWeh), or plutonium destruction, COP(k$/kg), are used as main figures-of-merit, these object functions primarily provide a means to identify important cost drivers and related tradeoffs and sensitivities to aid in the selection of key ATW technologies, approaches, and operating regimes. The absence of an ATW engineering design, even at a pre-conceptual level, and the highly integrated ("top-level") nature of the cost-estimating relationships (CERs) used in this study creates a high degree of risk for any bottomline cost comparison with more advanced fission technologies, although every effort has been made to incorporated realism into the CERS used. The cost-based ATW Systems Code (ATWSC) has been developed with an emphasis on broad parametric searches and cost-based optimizations to provide design guidance. The ATWSC cost and engineering models are described in Sec II., and fruitful development directions are suggested based parametric sensitivity studies reported in Sec. III. When possible, this cost-based systems study is guided by more detailed neutronics[1] and thermal-hydraulic[2,3] modeling of the ATW aqueous-slurry blanket, as well as using CERS developed in connection with projections made for other advanced energy systems.[4-6] Section IV. gives a summary and conclusion based on these limited studies of an ATW that generates net-electric power from spent LWR fuel without the creation of long-lived radioactive waste.

II. MODELS

A. Overview

The essential elements of the ATW systems being model by ATWSC are illustrated in Fig. 1. The ATWSC is a Fortran-based "search-and-scope" computer model that performs a two-parameter evaluation over a range of target-neutron production rates, YLD(mole/yr), and the final energy, E_B(MeV), of the proton beam impinging on a high-Z spallation target. The connection with beam current, I_B(A), or beam power, P_B(MW) = $I_B E_B$, is made through the neutron yield per incident proton, $Y(n/p) = (E_B - E_B^o)/y$, since YLD - $I_B Y(E_B) = P_B(1 - E_B^o/E_B)/y$, where E_B^o(MeV) and y(MeV/n) are fitting constants derived from separate transport computations.[1,7] The computational algorithm used in ATWSC connects parametrically through size and cost scaling relationships each of the main ATW subsystems depicted on Fig. 1. Table I lists key (fixed) input variables and associated notation. For given values of YLD and E_B, a simplified neutron balance and inputed value for the blanket neutron multiplication, kc., determine the rates of actinide fission, R_{ACT}(kg/yr), fission-product transmutation, R_{FP}(kg/yr), and loss of both accelerator-generated and fission neutrons to leakage and parasitic absorption. Through the use of input variables from detailed neutronics computations,[1] the generation of internal radioactive waste is also determined and incorporated into the assessment of overall system performance and cost. Simplified costing and engineering models are described in the following subsections for each of the major components indicated on Fig. 1. Application of appropriated factors for contingency, operation-and-maintenance, capital-replacement, and spare-component costs, along with indirect cost factors, allows a levelized annual charge, AC(M$/yr), to be estimated, which for a given net production(destruction) rate, P_E(MWe) or R_{ACT}(kg/yr), the COE(mill/KWeh) or the COP(k$/kg) is estimated as

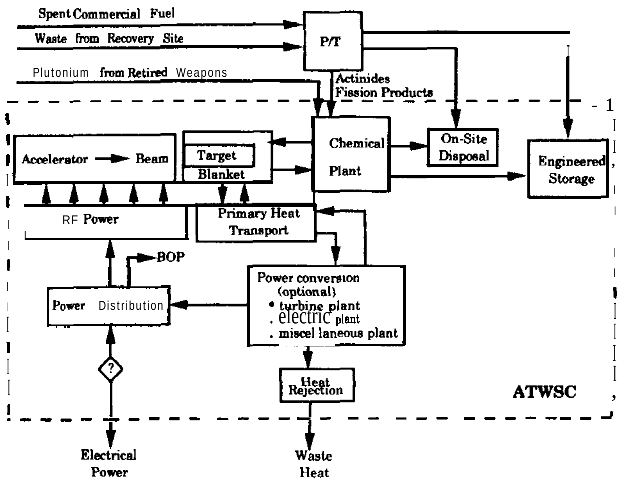

Figure 1. ATW Systems Code (ATWSC)

a function of plant capacity, YLD(mole/yr) [or, equivalently, net-electric power, P_E, or actinide destruction rate R_{ACT}]. The cost-based tradeoffs as a function of key design variables listed on Table I then result.

B. Costing

The financial parameters used to estimate levelized life-time costs are summarized in Table II. These costs are organized in accounts that parallel closely those used to assess advanced nuclear power systems[6,8] and, along with the main CERs, are summarized in Table III. All unit costs used in this study optimistically take "learning-curve" credits,[12] which for a cost reduction factor of 0.90 for each doubling of production would lead to a 50% cost reduction after three doublings; since after three generations (doublings) the eighth unit emerges, this factor of-2 cost credit is loosely called the "tenth-of-a-kind" assumption. Generally, the values and procedures reflected in Tables II and III are used in this study to facilitate comparisons on a common basis with other advanced nuclear power technologies.[4,6,8]

The CERS listed in Table HI correspond to highly integrated unit costs which, when combined the appropriate extensive parameter (length, mass, power, etc.), give the direct cost for the installed item in question. The CERS for the Primary-Heat-Transport, Turbine-Plant-Equipment, Electric-Plant-Equipment, and Miscellaneous-Plant-Equipment cost accounts in Table III represent scalings derived from more detailed cost breakdowns of these more-or-less conventional balance-of-plant systems.[5] The Accelerator Subaccount 22.1. and the Chemical-Plant-Equipment Account 27. are new additions to this otherwise standard nuclear utilities cost-accounting system. The CERS for the former are adapted directly from earlier work,[9,13] whereas total costs projected for a number of fuel-reprocessing plants have been normalized to a common reference year (1991) and scaled with plant capacity (kgHM/yr) to give the Account 27. CER listed in Table III.

Table I. Summary of Key Fixed Input to ATWSC.

parameter	value
ACCELERATOR (also Table IV)	
"Real-estate" gradient, G(MV/m)$^{(a)}$	1.0
Cosine of rf/beam-bunch phase angle, cos ϕ	0.866
Shunt resistance, R_s(Mohm/m)$^{10,(a)}$	36.7 -2400./E_B^{ccl}
DTL length, ℓ_{DTL}(m)	12.
Number of front-end legs, N_{FE}	2
ac→dc conversion efficiency, η_{DC}	0.95
dc→rf conversion efficiency for CCL, η_{RF}	0.65
dc→rf conversion efficiency for FE, η_{RF}	0.90×η_{RF}
waveguide→beam efficiency, η_{WG}	0.95
auxiliary power, P_{AUX}^{ACC}(MW)	20.
TARGET/BLANKET	
Neutron yield, Y(n/p)	$(E_B - E_B^o)/y$
• E_B^o(MeV)	177.4
• y(Mev/n)	35.4
Blanket neutronics	
•capture-to-fission ration, a	1.60
•average neutrons per fission, v	3.0
•non-leakage prob., P_{NL}^{J}(j = tar., blk.)	0.99/0.98
•neutron multiplication, $k_{eff} = (M_N - 1)/M_N$ $^{(a)}$	0.95
Thermal mass power density, MPD(MWt/tonne)	10.0
PLANT	
Availability, pf	0.75
Balance-of-plant auxiliary power fraction, f_{AUX}	0.02
Thermal-to-electric conversion eff., $\eta_{TH}^{(a)}$	0.30

(a) basecase values subject to parametric variation.

Using any one of the Table III CERS and the appropriate extensive property, a total installed cost for ATW is generated. Multiplication of these costs, including account-specific contingency and management factors, by appropriate total project contingency, replacement, and spare-component factors (Table II) gives the direct capital cost. Applying the financial parameters listed in Table II, after the addition of indirect costs, the levelized lifetime total cost for the escalation, inflation, and lending rates indicated on Table II is expressed as an annual capital charge. Adding the annual charges associated with operations gives the total annual charge, AC(M$/yr), from which the various unit costs of neutrons produced, CON(M$/mole), net-energy generated, COE(mill/kWeh), or actinide destruction, COP(k$/kg), used as main object functions are determined. The financial basis used here is that recommended for comparison advanced nuclear power stations.[4,6,8] All costs quoted herein are on a constant-dollar basis[6,8] and reflect the above-mentioned "10th-of-a-kind" assumption. These costs are expressed in 1991 dollars, although within the accuracy of the highly integrated CERS and for the relatively low inflation rates over the last few years, quoted cost can be considered to have a 1991-92 basis.

TABIE II FINAN CIA L PARAMETERS

Plant operating lifetime, T_{LIF}(yr)	30.
Plan t construe tion time, L(yr)	10.
Capacity'availability factor, p_f	0.75
Inflation rate, i(1/yr)	0.03
Escalation rate, x(1/yr)	0.03
Capitalization (utility) fractions	
• Debt	0.50
• Preferred divident	0.10
• Common equity r etur n	0.40
Return on capitalization	
• Debt interest (1/yr)	0.097(0.045) (a)
• Preferred dividend (1/yr)	0.090(0.038) (a)
• Common equity retur n	0.140(0.086) (a)
Avg. cost of mone y, X. (1/yr, AFUDC) (a)	0.1135(0.06115)
Federal income -tax rate (1/yr)	0.35
State income -tax rate (1/yr)	0.04
Effective fed. and state income -tax rate, t(1/yr)	0.3664
Eff. cost of mon ey (disc. rate), X(1/yr)	0.0957(0.0435) (a)
Local property tax rate (1/yr)	0.02 (b)
Tax depreciation life (yr)	15. (c)
Interim replacement rate (1/yr)	0.005
Cons tant-dollar- year	1990-91
Fixed charge rate, FCR(1/yr)	0.0%560(0.1638) (e)
Interest during const. factor, I DC	0.1652(0.3178) (e)
Escalation during const. factor, EDC	0.0(0.2436) (e)
Contingencies	
• accelerator	
- DTL + RFQ	0.35
- CCL	0.45
- rf power	0.35
• tar ge t/blan ket	0.40
• chemical plant equipment	0.35
• balance of plant	0.15
• overall project	0.10
• annual charges	0.15
Operation and Maintenance (O&M) factors	
• accelerator	0.02
• tar ge t/blan ket	0.05
• chemical plant equipment	0.02
• balance of plant	0.02
Capital upgrade factors	
• accelerator	0.02
• tar ge t/blan ket	0.05
• chemical plant equipment	0.05
• balance of plant	0.02
Spares factor	
• accelerator	0.02
• tar ge t/blan ket	0.05
• chemical plant equipment	0.05
• balance of plant	0.02

(a) real (inflation adjusted) parameters.

(b) rate applied to initial investment with no escalation due to inflation or decreases due to depreciation.

(c, from appropriate tax schedules

(d) percent of initial investment paid out each year for miscellaneous replacement; assumed to escalate at the general rate of inflation.

(e) con stant (nom inal)-dol lar values.

TABLE [11 COST Estimating RELATIONSHIPS

	Accounts	CER(a)
20.	Land	10.
21.	Site	
21.1.	Buildings	
21.1.1.	Support Buildings	5.[9]
21.1.2.	Tritium Vault	15.[9]
21.2.	Electricity	
21.2.1.	Power Lines	$2.5 + 7.5P_{EA}/770.$[9]
21.2.2.	Substation	$3.75 + 11.25P_{EA}/770.$[9]
21.3.	Water	
21.3.1.	Water Plant	$1.25 + 3.75P_{TH}/687.$[9]
21.3.2.	Cooling Tower	$3.75 + 3.75P_{TH}/687.$[9]
21.4.	Security	10.
21.5.	Miscellaneous	10.
22.	Accelerator/Reactor Plant Equip.	
22.1.	Accelerator	
22.1.1.	CCL Structure	$0.15\ell_{CCL}$ [10]
22.1.2.	RF Power	$2.00P_{RF}$ [10]
22.1.3.	Front-end	50.[10]
22.1.4.	Tunnel	$3.75 + 11.25E_B/1600.$
22.1.5.	Refrigeration (SC CCL)	$P_{RFG} = 10.[1 + (G/5)^2]\ell_{CCL}/10^6$,[10] $UC_{RFG} = 300$ M$/MW
22.1.6.	Pulsed ETS (pulsed CCL)	$UC_{ETS}P_{RF}/f$, $UC_{ETS} = 1.0$ M$/MJ
22.1.98.	Spares	2.0% Acct. 22.1.
22.2.	Target/Blanket Systems	
22.2.1.	Tar./Blk. 10. MWt/tonne, U_{TB} = 100 $/kg	
22.2.2.	Prim. Ht. Tran.	$400.(10^6P_{TH})^{0.55}/10^6$ [5]
22.2.3.	Tar./Blk. Bldg.	100.(b)
22.2.98.	Spares	5.0% Acct. 22.2.
23.	Turbine Plant Eq.	$7.02(10^6P_{ET})^{0.83}/10^6$ [5]
23.98.	Spares	2.0% Acct. 23.
24.	Elec. Plant Eq.	$4262.(10^6P_{ET})^{0.49}/10^6$ [5]
24.98.	Spares	2.0% Acct. 24.
25.	Misc. Plant Eq.	$252.(10^6P_{ET})^{0.59}/10^6$ [5]
25.98.	Spares	2.0% Acct. 25.
26.	Special Materials (Li coolant, molten salt, etc.)	
27.	Chemical Plant Equipment	
27.1	FP/Struct. Process.	$9.41(R_{ACT} + R_{FP})/f_{BU})^{0.4}$[11]
27.2.	Tritium Process.	25.(b)
27.98.	Spares	5.0% Acct. 27.
90.	Total Direct Cost (TDC, sum of above)	
91.	CS&E	10.0% Acct. 90.
92.	HOE&S	10.0% Acct. 90.
93.	FOE&S	10.0% Acct. 90.
94.	Owner's Costs	5.0% Acct. 90.
95.	Process Contingency (not used)	
96.	Project Contingency	10.0% Acct. 90.
97.	Int. During Const. IDC,	16.53% Accts. 91. → 96.
98.	Est. During Const. EDC,	0.0% Accts. 91. + 96.
99.	Total Cost (TC), sum of above	

(a) all costs in M$, powers in MW, and time in years.
(b) Based on Tritium Systems Test Assembly.

C. Engineering

The engineering basis of the ATWSC is derived more from engineering judgment than from a firm engineering design. Engineering models that provide parametric input to the CERs are heuristic and highly integrate. The size and performance of each main subsystem depicted in Fig. 1 is first estimated. The basis of this estimate is primarily the power balance illustrated in Fig. 2., which includes an approximate neutron balance used to match accelerator requirements to specific transmutation and fission rates. For all computation reported herein, the total thermal power delivered for thermal-to-electric conversion is optimistically taken as $P_{TH} = P_{BLK} + P_B$, where the power delivered to the target by a proton beam of energy E_B(MeV) and current I_B(A) is P_B(MeV) = $I_B E_B$. For all cases considered, $P_{FISS} = P_{BLK}$.

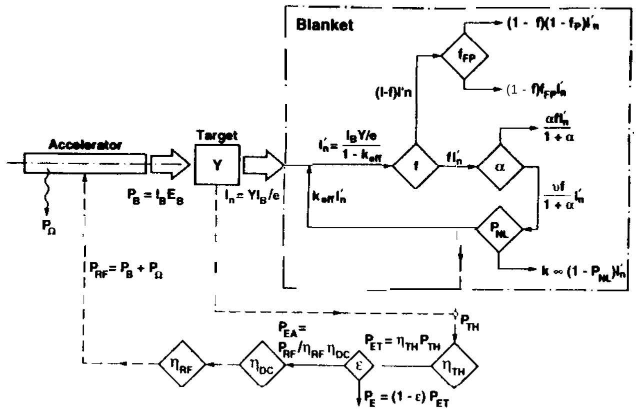

Figure 2. ATWSC power and neutron balances.

1. Accelerator. Power consumed in the generation, transport, and conversion of beam kinetic energy represents a major component of the recirculating power fraction. Table IV gives the efficiencies η_{DC}, η_{RF}, and η_{WG} associated with the generation and transport of rf power to the accelerator *per se*. The rf → beam coupling efficiency is modeled as $\eta_B = 1/(1 + I^*/I_B)$, where $I^* = G/(R_s \cos\phi)$ and front-end (RFQ, DTL, and BCDTL) losses are accounted separately. In the above expression, $\eta_B = P_B/(P_B + P_\Omega)$ is ratio of final beam power to beam plus cavity Ohmic losses, G(MV/m) is the "real-estate" field gradient in the CCL, ϕ is the phase angle between beam bunch and accelerating voltage, and a nominal (average, effective) shunt resistance is R_s(MV/m).

The accelerator model accounts separately for the front-end (FE) and the CCL losses, following the beam-energy and power splits between RFQ, DTL, BCDTL, and CCL parts of the accelerator, as listed in Ref. 10. Figure 3. illustrates this division, with the model described below separating FE into FE1 (RFQ + DTL) and FE2 (BCDTL) components. The efficiency with which rf power is translated into beam power is described by a local (FE1 or FE2) coupling efficiency, $\eta_B^{FEj} = 1/(1 + I^*_{FEj}/I_B)$, with the parameters I^*_{FEj} (j=1,2) being determined from the FE beam and cavity-loss powers report in Ref. 10. These and other parameters for the accelerator with resolved FE losses are listed in Table IV.

Table IV. Accelerator Parameters [10] Used in ATWSC.

parameter	values		
Acc. component, j	RFQ + DTL	BCDTL	CCL
Added energy, E_{Bj}(MeV)	20.	60.	1,520.
Coupling eff.(a)	0.5952	0.7143	0.8526
Coupling param. I^*_{Bj}(A)(a)	0.0085	0.1021	0.3282(b)

(a) $\eta_{Bj} = 1/(1 + I^*_j/I_B)$; $I^*_j = G/(R_s \cos\phi)$; I_B = 0.25A
(b) this case pertains to R_s being a function of CCL beam energy, E_B^{ccl}, which for $R_s = 36.70 - 2400.0/E_B^{ccl}$ corresponds to R_s = 35.12 Mohm/m for E_B^{ccl} = 1,520 MeV (E_B = 1,600 MeV)

Separation of accelerator Ohmic losses into FE = FE1 + FE2 and CCL components leads to the following expression for the ratio of final beam power, $P_B = E_B I_B$, to total rf power delivered to the accelerator cavities:

$$\eta_B = \frac{1 + E_B^{FE}/E_B^{ccl}}{1/\eta_B^{ccl} + (E_B^{FE}/E_B^{ccl})/\eta_B^{FE}}, \quad (1)$$

where $E_B = E_B^{ccl} + E_B^{FE}$, $E_B^{FE} = E_B^{FE1} + E_B^{FE2}$, and the following expressions give η_B^{ccl} and η_B^{FE}:

$$\eta_B^{ccl} = \frac{1}{1 + I^*_{ccl}/I_B} \quad (2)$$

$$\eta_B^{FE} = \frac{1 + E_B^{FE2}/E_B^{FE1}}{1 + \eta_B^{FE1} + (E_B^{FE1}/E_B^{FE2})/\eta_B^{FE2}}. \quad (3)$$

The E_B dependence of R_s for the CCL, as determined by detailed beam-dynamics simulations, [10] is R_s(MOhm/m) = $36.70 - 2{,}400.0/E_B^{ccl}$.

Figure. 4A. plots the overall accelerator "wall-plug" efficiency, $\eta_A = \eta_{DC}\eta_{RF}\eta_{WG}\eta_B$, as a function of E_B, I_B, and P_B. Generally, the efficiency of proton production increases for a given neutron production rate, YLD(mole/yr) - P_B, with increased beam current and, hence, decreasing beam energy. While the operational limits on total beam current will hopefully continue to be pushed upward, the impact of I_B limits

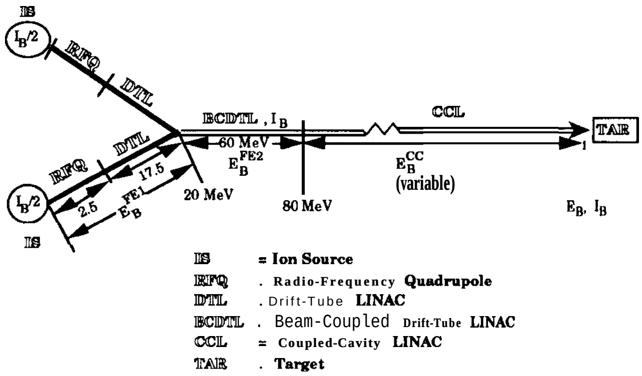

Figure 3. ATWSC accelerator model.

on η_A is also shown on Fig. 4A. Since the primary product of the ATW is neutrons rather than protons, a more relevant measure of system performance from the accelerator view point is the energy invested to create each target neutron, En(MeV/n) = $E_B/\eta_A/Y$. Figure 4B. gives the dependence of En on E_B and P_B, showing a minimum results from the tradeoff of increasing Y and decreasing η_A as E_B increases for a given P_B; this minimum decreases and shifts to higher beam energies as the system capacity, YLD(mole/yr) = $326.5P_B(1 - E^o_B/E_B)/y$ increases. If the energy investment EN is to represent a fraction ε of the total electrical energy generated from this neutron, $E_F M'_N \eta_{TH}$, where E_F = 200 MeV/fission is the fission energy, η_{TH} - 0.30 is the thermal-conversion efficiency, and $M'_N = k_{eff}/(1 - k_{eff})$ is the power multiplication, than for EN = 100 MeV/n and $\varepsilon < 0.2$, if follows that $M'_N > 8$, or k_{eff} >0.90. This result is approximate, with optimizations based more self-consistently on economic analyses indicating in Sec. III. $k_{eff} > 0.95$ being more desirable.

2. Target/Blanket. A conceptual engineering design of the electric-power-producing ATW target-blanket (TB) system has not been made, although a number of heavy-water moderated/aqueous-slurry concepts have been subject to parametric elaboration,[3] and a pre-conceptual design of a low-efficiency case has been reported.[2] The parametric study of a range of aqueous-slurry concepts have indicate thermal mass power densities in the range MPD = 30-40 MWtftonne, where MPD is the ratio of blanket thermal power to blanket mass. Accounting for added structure that a detailed design would inevitably identify, as well as added conservatism injected into the design of a pressure vessel that operates in an intense neutron radiation field, MPD = 10 MWt/tonne is assumed. This compares to -3 MWt/tonne for a 1-1.2 GWe PWR, and a factor of 2-3 less for conventional heat exchangers. The higher MPD values adopted for the ATW reflects a need to reduce total (in-blanket + exe-blanket) slurry inventories to preserve an important merit of the ATW approach to actinide transmutation and associated power generation.[3] Given the goal MPD for the ATW

TABLE V OPTIMIZED ECONOMIC AND PERFORMANCE PARAMETERS USED AS "POINT-OF-DEPARTURE" CASE

Parameter	Value	
Ace. neutron yield, YLD(mole/yr)[(a)]	1,350.	
Beam current, I_B(mA)	228.	
Beam energy, E_B(MeV)	820.	
Beam power, P_B(MW)	187.	
Accelerator power, P_{EA}(MW)	372.	
Total thermal power, P_{TH}(MW)[(b)]	5,604.	
Total electric power, P_{ET}(MW)	1,681.	
Net electric power, P_E(MW)	1,220.	
Recirculating power fraction, $\varepsilon = 1/Q_E$	0.2728	
Accelerator efficiency, $\eta_A = P_B/P_{EA}$	0.5011	
Plant efficiency, $\eta_p = \eta_{TH}(1-\varepsilon)$	0.2182	
Num. 1000-MWe LWRS supported, N_{SUP}	6.4	
Actinide burn rate, R_{ACT}(kg/yr)	2,081.	
Top-level direct costs (M$)		
•Land and Privileges, Acct. 20.	10.	[0.3][(c)]
•Site, Acct. 21.	89.	[2.9]
•Acc./Reactor Plant Eq., Acct. 22.	1,209.	[39.01
- Accelerator, Acct. 22.1.	923.	[29.7]
- Target-Blanket Systems, Acct. 22.2.	287.	[9.31
• Turbine Plant Equipment, Acct. 23.	439.	[14.2]
•Electric Plant Equipment, Acct. 24.	195.	[6.3]
•Misc. Plant Equipment, Acct. 25.	96.	[3.1]
•Special Materials, Acct. 26.	0.	[0.0]
•Chemical Plant Equip., Acct. 27.	1,058.	[34.2]
• Total Direct Cost, Acct. 90.	3,097.	
Total Cost, Acct. 99.	5,238.	
Unit Costs		
•Cost of Electricity, COE(mill/kWeh)	56.5	
•Unit Direct Cost, UDC($/We)	2.53	
•Unit Total Cost, UTC($/We)	4.29	
•Cost of "product," COP(k$/kg)	136.8	
Annual charges, AC(M$/yr)	454.	
•Capital	217.	
•Operating	237.	
Present worth of charges (B$)	18.14	
•Total capital	8.67	
•Total operating and maintenance	9.37	
•Fuel	0.0	
• Decontamination/decommissioning	0.10	
Present worth of revenues (B$)[(d)]	12.73	

(a) YLD $\simeq I_B Y(3.15 \times 10^7)/eN_A$ =

$P_B(1 - E^o_B/E_B)/y/(eN_A/3.15 \times 10^7)$

= 326.4 $P_B(1 - E^o_B/E_B)/y$; E^o_B = 177.35 MeV and y = 35.4 MeV/n are target-yield fitting parameters for an off-set-linear function of Y(n/p) with EB. (Table I)

(b) target plus blanket powers.

(c) percentage of total direct cost.

(d) value of electrical energy over lifetime of plant if sold at COE* = 50 mill/kWeh.

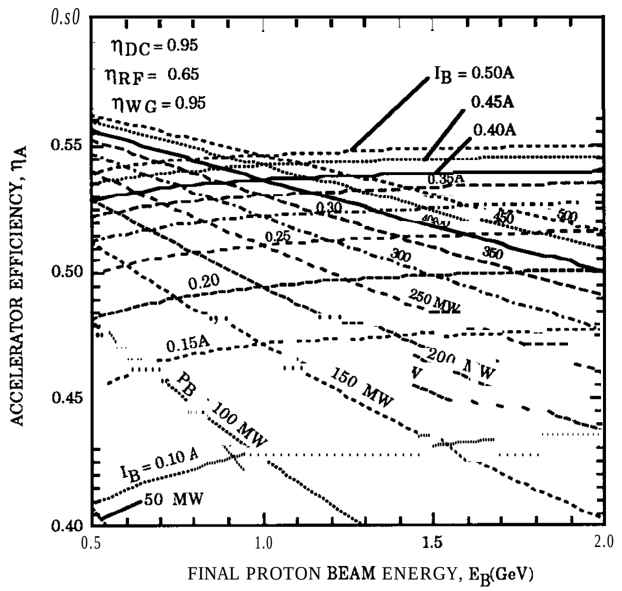

Figure 4A. Dependence of accelerator efficiency on beam energy for fixed beam power or current.

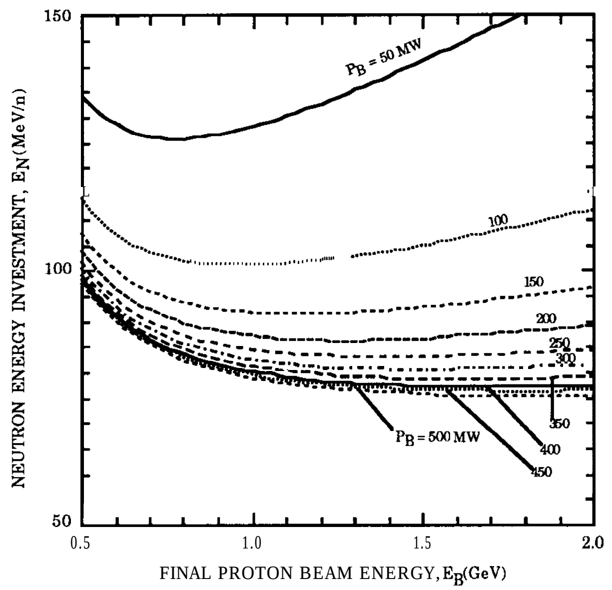

Figure 4B. Dependence of energy invested per neutron generated on proton-beam energy and power.

target-blanket system and an appropriately escalated unit cost ($/kg) for this advanced system, the dependence of total TB direct cost on capacity can be estimated; the magnitude of the contingency (Table II) applied to this or any other ATW system is used to reflect the cost impact of striving for non-conventional goals in a given system in order to assure specified performance [e.g., high slurry power density, $q(\mathrm{MW/m^3})$, or reduced actinide inventory, $I_{ACT}(\mathrm{kg})$] goals.[3]

Whether the aqueous-slurry blanket assumes an out-of-blanket heat-exchanger (OBHX), in-blanket heat-exchanger (IBHX), or a Boiling-Water Slurry (BSW) configuration,[3] a Primary Heat-Transport (PHT) system consisting of primary and secondary pumps, intermediate heat-exchangers (or condenser-evaporators), pressurizerlsurge-tank, and associated piping to and from a heavily shielded TB system will be required. As is indicated in Table III, a highly integrated (lumped) CER is used for the complete PHT system that supports each of N_{BLK} blankets. The lack of a TB/PHT layout with which to estimate the length of pipe runs, the size of equipment rooms, the thickness of radiation shielding, or the impact of maintenance schemes on equipment placement introduces large uncertainty into the ATWSC results, since both the direct and indirect cost impacts of piping requirements can be large.

3. Chemical Plant. Like the Accelerator (Account 22. 1.), the Chemical Plant Equipment (CPE, Account 27.) represents a new addition to the more conventional nuclear power plant cost accounting system adopted by the ATWSC. Also, like the target-blanket component of the Reactor Plant Equipment (RPE, Account 22.2.), little or no detailed design exists for the CPE. Concern about excessive costs of radiochemical plants were prevalent in early assessments of nuclear-power economics,[14,15] and those concerns prevail today.[11,16] The CER for the CPE listed in Table III is of the form $UC_{CPE}(\mathrm{M\$/kgHM/yr}) - [CAP_{CPE}(\mathrm{kgHM/yr})]^{\nu}$, where the fitting constants are derived from cost projections of nearly a dozen radiochemical and fuel-reprocessing plants. The capacity, $CAP_{CPE}(\mathrm{kgHM/kg})$, when applied to the ATW, is based on the actinide and fission-product transmutation rates, $[R_{ACT} + R_{FP}](\mathrm{kg/yr})$, divided by an effective LWR burnup fraction, f_{BU}, corresponding to a fuel exposure of 33 GWtd/tonne, thereby converting the capacity to an equivalent heavy metal for which the UC_{CPE} scaling was derived.

Scaling the CPE costs for ATW solely on the basis of mass capacity is characterized by uncertainties related to the unique characteristics of the high-throughput, high-burnup ATW system. 17 Since much of the CPE equipment should scale with volumetric throughput of solvents, and given similar specific (decay) power-density limits are imposed on similar solvents (-10 W/litre), the volumetric throughput per unit mass throughput in certain parts of the CPE system may be larger. Until the CPE system for ATW is better defined so that tradeoffs related to the cost of process rates (dilution) versus the cost of holdup (increased storage and inventory) can be quantified, the CPE is costed on the basis of mass throughput (Table III).

4. Balance of Plant. The fidelity available to project the cost of balance-of-plant items (Accounts 23.-26.) is much greater than is required by the present analysis. Hence, for the purposes of this study, lumped CERs are used for the Turbine Plant Equipment (Account 23.), the Electric Plant Equipment (Account 24.), and the Miscellaneous Plant Equipment (Account 25.);[5] for the present design, no Special Materials (Account 26.) are envisaged.

IV. RESULTS

The results from a single, COE-optimized **ATWSC** scan of capacity, **YLD(moles/yr) ~ P_B(MW)**, and beam energy, **E_B(MeV)**, are first given. The cost sensitivities for an ATW of a given net-power output, **P_E(MWe)** = 1,220 MWe, and blanket neutron multiplication, **M_N** = $1/(1 - k_{eff}) = 20$ ($k_{eff} = 0.95$), to key engineering variables are then summarized; this base or "**point-of-**departure" case corresponds to an actinide destruction rate of **R_{ACT}** = 2,080 **kg/yr** or the equivalent annual discharge from **N_{SUP}** = 6.4 **1,000-MWe** LWRS. For all the cost-based results given the impact (distortion) of the capacity-dependent CERS used must be recognized; while unit costs that are "competitive" with projections for advanced nuclear systems may be achieved at large capacity, the limits of "economies-of-scale" rules and the inevitable transition into the region of "diseconomies of scale" (i.e., projecting too far ahead of the "learning curve") should be kept in mind. Furthermore, when comparing an ATW system that offers solutions to problems not addressed by advanced nuclear power plants, the issue of "competitiveness" becomes somewhat fuzzy and goes beyond the level of economics on which this study is based.

A. Base Case

Figure 5 gives the cost *versus* capacity (**YLD**, P_B, **R_{ACT}** or P_E) tradeoff with accelerator beam energy and current. The minimum-COE trough indicated on Fig. 5A slopes downward as capacity increases, with the contours of constant COE being given on Fig. 5B. For a more explicit display of cost tradeoffs and relative magnitudes, either the net-electric power, **P_E(MWe)**, or the number of 1,000-MWe **LWRs, N_{SUP} = P_{SUP}(GWe)**, are used interchangeably. Figure 6A gives the dependence of direct cost for each major cost category on P_E; the scaling of COE is also shown. The major direct costs are incurred for the Reactor Plant Equipment (**RPE**, Account 22.) and the Chemical **Plant** Equipment (**CPE**, Account 27.) accounts. The companion Fig. 6B gives the **subaccount** breakdown for Account 22., with the cost of rf power being the dominant **subaccount**. The dependence of COE and P_E on **N_{SUP}** is shown on Fig. 7 for the basecase copper-cavity CCL, as well as for a superconducting CCL and a CCL with layered dielectric rings[18] to reduce 'cavity losses; the weak COE dependence for these advanced accelerators is addressed in the following subsection.

A "point-of-departure" case is identified on the basis of the maximum capacity net-electric power of P_E = 1,220 MWe. The cost-account breakdown and key parameters for this case are summarized in Table V and Fig. 8. This case provides a basis about which COE sensitivities to key parameters are elaborated. The COE -56.5 **mill/kWeh** (constant-dollar) unit cost (COP = 135 **k$/kg**) is -1.4 times higher than that for an **advanced** nuclear system predicted on nominally the same basis.[4]

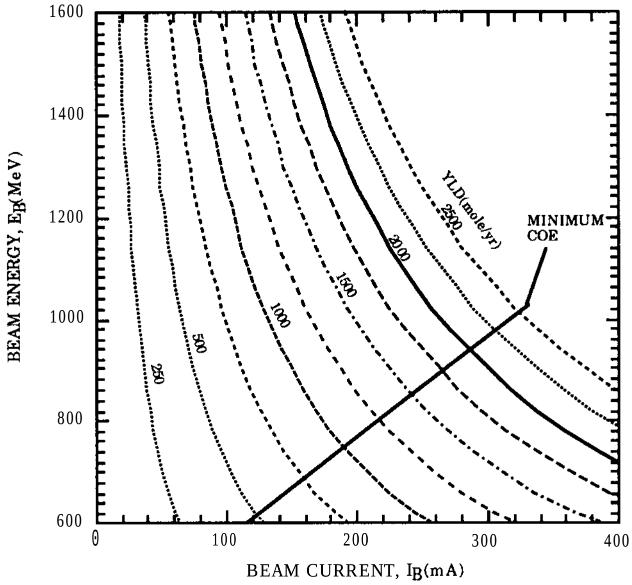

Figure 5A. Dependence of beam current on beam energy for a ranged of target-neutron production rates.

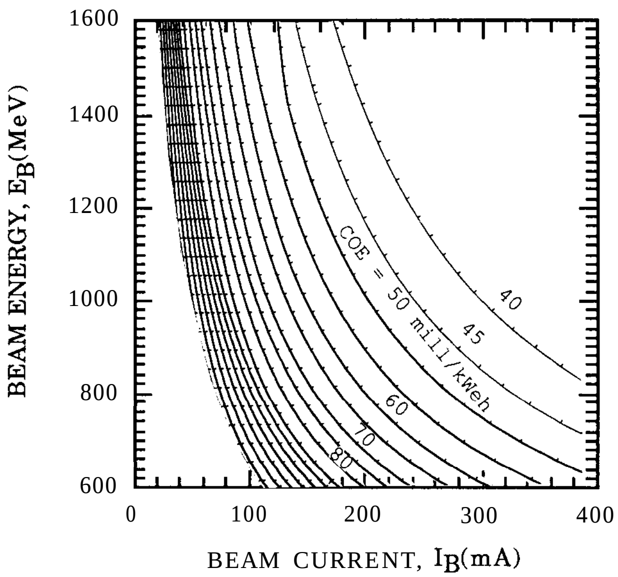

Figure 5B. Dependence of beam current on beam energy showing **contours** of constant COE.

B. Parametric Sensitivities

1. Accelerator. As shown in Fig. 7, reduction of CCL cavity losses by invoking either superconductivity or layered dielectric structures has little impact on COE. The added cost of a superconducting CCL structure, in fact, leads to a somewhat higher COE (-2%) than the copper-CCL base case, despite the elimination of all **cavity** eddy-current losses. A potential saving in rf power is seen from the layered-dielectric case, where energy savings are accrued without increasing the unit cost of CCL structure (**R_S** + 100xRJ; in this case the

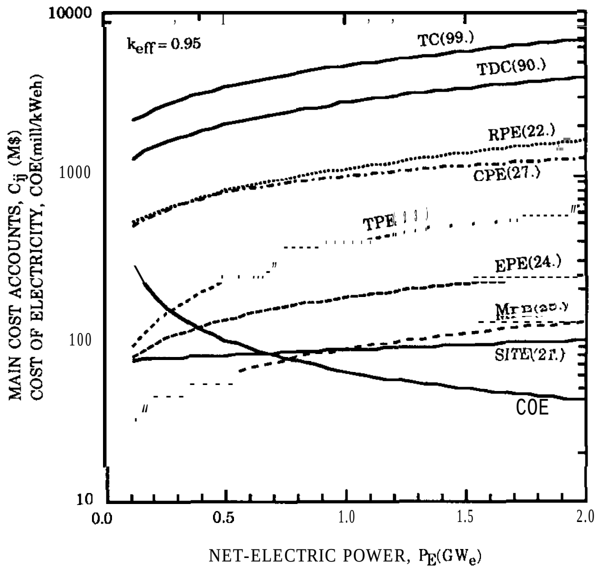

Figure 6A. Dependence of major cost accounts on net-electric power under minimum-COE conditions.

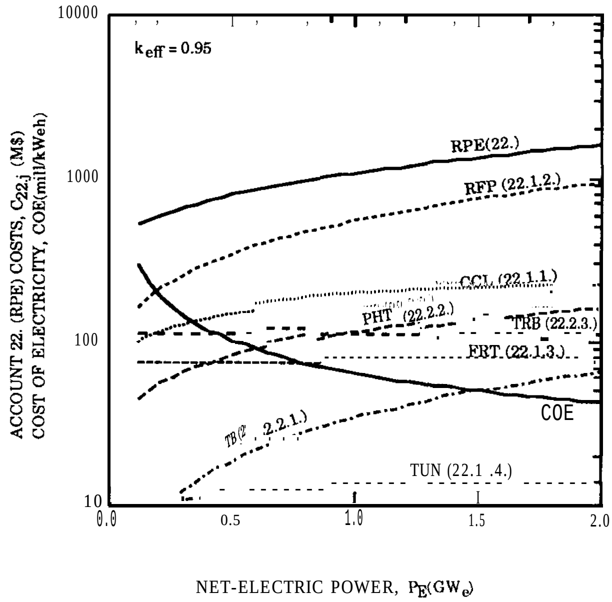

Figure 6B. Dependence of Account 22. items on net-electric power under minimum-COE conditions.

COE is reduced by only ~3%. These small economic benefits occur because these accelerator advances impact only the ~15% of the total rf loss occurring in the CCL structure; while rf-power costs are a major component of the RPE Account 22. (-30%), it is a lesser fraction of the total direct cost(~20%), and most of these costs are incurred in providing for rf-related losses in conversion and transport process prior to injection into the CCL cavity. The issues of CCL design complexity, cost, access, and overall availability (mean-time-to-repair *versus* mean-time-to-repair) for these advanced CCLS may also be important. Furthermore, the large impact of the CPE Account 27. (34% of total direct costs, Table V) for all cases examined distorts this and other cost sensitivities.

2. Target-Blanket. For the target-blanket mass power density (MPD = 10 MWt/tonne) and unit cost (UC_{TB} = 100 $/kg) assumed, the blanket has little direct cost impact (1.370 of total direct cost), although the supporting primary-heat-transport (PHT) system amounts to - 10% of direct costs. The main impact of the TB system is through the reduction in accelerator requirement as $M_N = 1/(1 - k_{eff})$ is increased and through increases in thermal-conversion efficiency, η_{TH}, possible through higher temperature operation. The cost impact of increased k_{eff} is shown on Fig. 9; given the upper limit assumed for the basecase capacity (P_E = 1,220 MWe) and the target neutron-yield scaling used, blanket multiplications of MN > 20 (k_{eff} > 0.95) are desirable. The issue of optimum η_{TH} is more difficult to resolve,[3] since neutronic and economic penalties are encountered if η_{TH} is pushed to far upward. As for the cost dependence on accelerator performance, these results are distorted by the large CPE costs and the relatively weak scaling of the associated unit cost with capacity compared to other ATW subsystems.

3. Balance-of-Plant. The impact of thermal-conversion efficiency, η_{TH}, and net-electric power, P_E, on COE is illustrated on a percentage basis relative to the "point-of-departure" case (Table V) on Fig. 10. Shown also is the cost impact of blanket multiplication, MN, as well as a reduction in CPE unit cost. Although large uncertainties are associated with the present cost analysis, on a relative basis and from the perspective of the electric-utility boardroom, changes of a few percentage points in COE are significant.

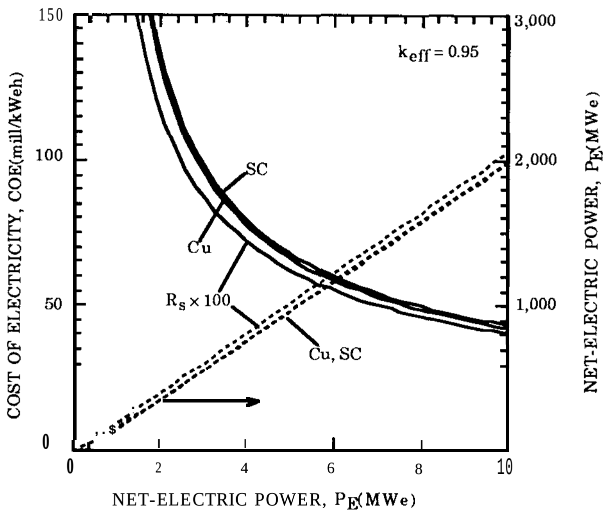

Figure 7. Scaling of basecase COE with capacity, P_E(MWe) and N_{SUP} for a range of CCL options.

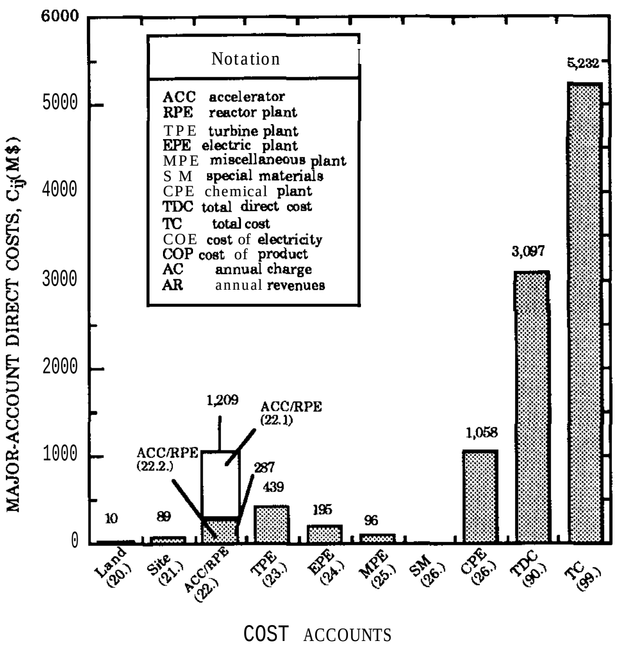

Figure 8. Capital cost breakdown for "point-of-departure" case listed in Table V.

Lastly, Fig. 11 examines the ATW purely from the view point of the economics of actinide destruction and the decision to invest in the capital equipment needed to convert thermal power derived therefrom to electricity for both internal consumption and for *revenue* generation. In this case, the net annual charge, AC_{NET}(M$/yr), and that number divided by the rate of actinide burnup, COP(k$/kg), are used as object functions. A breakeven point at R_{ACT} -330 kg/yr is indicate, above which investment in revenue-generating

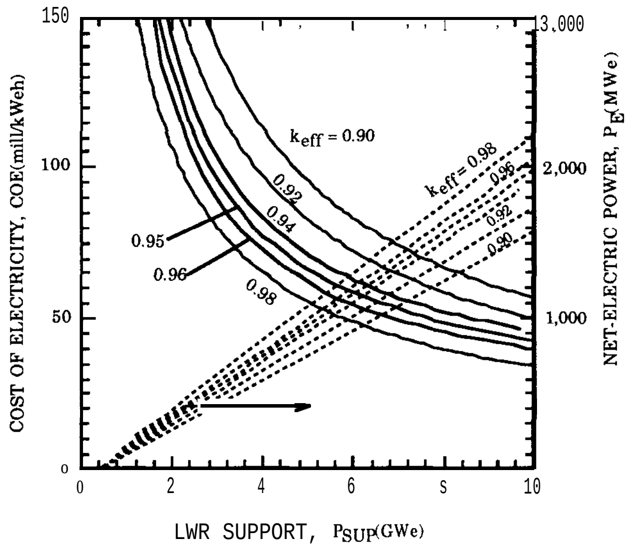

Figure 9. Dependence of basecase COE on capacity, P_E(MWe) and N_{SUP}, and k_{eff}.

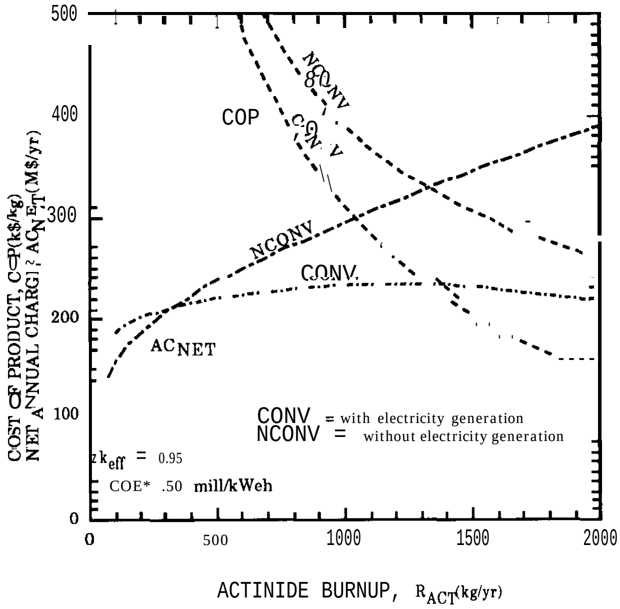

Figure 10. Dependence of costs to destroy actinide on burnup rate (capacity) with (CONV) and without (NCONV) generation and sale of electrical power.

electricity production would be profitable. For these case, the market value of electrical energy is taken as COE* = 50 mill/kWeh.

V. SUMMARY CONCLUSIONS

A comprehensive, but "top-level" (i.e., low-fidelity), cost-base parametric systems model of a net-power-producing ATW fueled with LWR spent fuel as been used to examine (primarily) subsystem cost impacts and sensitivities and to assess (secondarily) economic competitiveness as an electrical-power producer. Interim conclusions are as follows:

- direct costs are approximately equally distributed amongst Accelerator (Account 22. 1.), Chemical Plant Equipment (Account 27.), and Balance-of-Plant (Accounts 23., 24., and 25.) plus Target-Blanket (Account 22.2.) systems; no single subsystem is a strong cost driver.

- reductions in accelerator cost impact is most effectively implemented through efficient generation and transport of rf power to the CCL; advanced (superconducting or layered-dielectric) cavity designs may not be cost effective, particularly when designs are sufficiently detailed to assess the impact of accelerator repair time and availability.

- blanket multiplications MN > 20 (k_{eff} >0.95) are essential, but somewhat lower (than the η_{TH} = 0.30 basecase value) thermal-conversion efficiencies can be tolerated, particularly for systems with major CPE costs; more detailed designs are needed to assess the benefit-to-cost parametric for higher-η_{TH} systems.

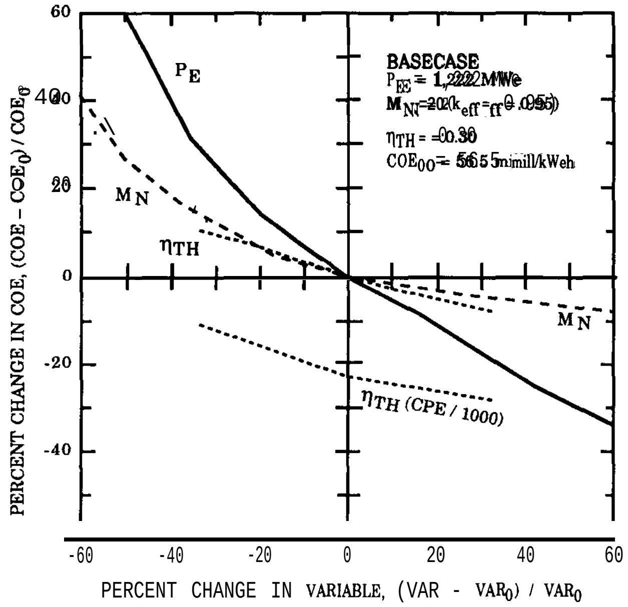

Figure 11. Normalized COE sensitivities about base case (Table V) for single-point variations in: net-electric power, P_E(MWe); blanket neutron multiplication, M_N; thermal-conversion efficiency, η_{TH}; and η_{TH} without cost impact of Chemical Plant Equipment, η_{TH}(CPE/1,000.)

- energy costs from a net-power-producing ATW are predicted to be 40-50% above advanced nuclear systems in the same capacity class (1.0-1.2 GWe); the incremental cost of electricity when spread over the N_{SUP} -6-8 client reactors amounts to 2-3 mill/kWeh; the main benefit for this more expensive power is the elimination of all long-term actinide and fission-product waste.

- electricity generation as a source of revenue is essential for all but the smallest ($N_{SUP} < 1$) of ATW designed to burn spend LWR fuel.

REFERENCES

1. W. C. SAILOR and C. A. BEARD, "Neutronic Analysis for an Accelerator-Based Nuclear Waste Transmuter," this conference.

2. M. CAPIELLO, J. IRELAND, J. SAPIR, and B. KROHN, " Los Alamos Aqueous Target/Blanket System Design for the Accelerator Transmutation of Waste Concept," *ibid.*

3. R. A. KRAKOWSKI, "Parametric Studies of Aqueous-Slurry Blankets of ATW," *ibid.*

4. J. G. DELENE, "Update Comparison of Economics of Fusion Reactors with Advanced Fission Reactors," Fus, Technol., 19(3,2A), 807 (1991).

5. R. L. MILLER, W. R. SPEARS, R. HANDOX, and R. A. KRAKOWSKI, "Comparison of EURATOM and U.S. Estimated of Fusion Reactor Costs," Fus. Technol., 19(3,2A), 813 (1991).

6. J. G. DELENE and C. R. HUDSON II, "Cost Estimate Guidelines for Advanced Nuclear Power Technologies," Oak Ridge National Laboratory report ORNIJI'M-1OO7VR2 (1990).

7. G. RUSSEL, personal communication, Los Alamos National Laboratory (1992),

8. "Nuclear Energy Cost Data Base, A Reference Data Base for Nuclear and CoalCoal-Fired Power Generation Cost Analysis," U.S. Department of Energy Office of Nuclear Energy report DOE/NE-0095(1988).

9. R. LeCLAIR, "Systems Design and Cost Analysis, " personal communication, Los Alamos National Laboratory, (September 7, 1989).

10. G. P. LAWRENCE, personal communication (October 26, 1992), also "The Los Alamos Accelerator Transmutation of Nuclear Waste (ATW) Concept," Los Alamos National Laboratory document ATW-92-60 (April 15, 1992).

11. "The Economics of the Nuclear Fuel Cycle," Nuclear Energy Agency, OECD (1985).

12. L. ARGOTE and Dennis EPPLE, "Learning Curves in Manufacturing", Science, 247,920 (1990).

13. Grumman Aviation Corporation, private communication, "Cost Study: Accelerator Production of Tritium" (May 5, 1989).

14. W. G. STOCKDALE, "Estimating Costs for Radiochemical Plants," Chem, Eng., 63, 185 (April 1956).

15. Division of Civilian Applications, AEC, "Summary Report: AEC Reference Fuel-Processing Plant," U.S. Atomic Energy Commission report WASH 743 (October 1957).

16. J. E. GINGOLD, R. W. KUPP, D. SCHAEFFER, and R. L. KLEIN, "The Cost of Processing Irradiated Fuel from Light Water Reactors: An Independent Assessment," Electric Power Research Instituted report EPRI NP-7264 (April 1991).

17. D. F. McLAUGHLIN, "Cost Estimation for ATW Chemical Processing Plant", private communication, Westinghouse Electric Corporation, (March 22, 1993).

18. W. C. SAILOR, F. M. MUELLER, and B. E. CARLSTEN, "Theory for a Cylindrical Pillbox Accelerator Cavity Using Layered Structures for Reducing Skin-Effect Losses," IEEE Trans on Microwave Theory and Techniques (August, 1993).