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SCALING AND COST TRADEOFFS FOR ATW: PRELIMINARY CONSIDERATIONS

Robert A. Krakowski

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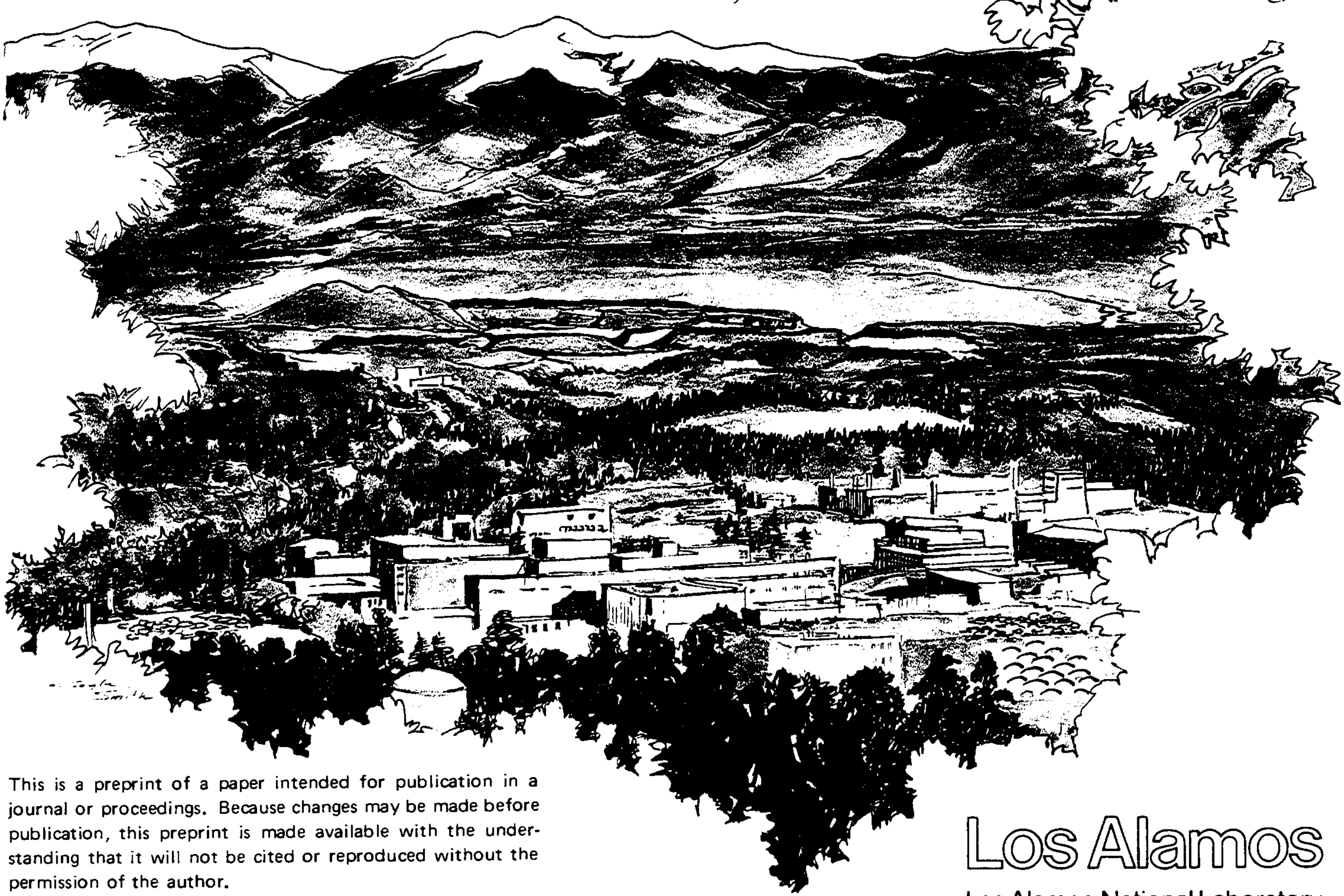

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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R. A. Krakowski

ABSTRACT

The use of accelerator-produced spallation neutrons to transmute actinide and long-lived fission-products portends a means to alleviate requirements for deep-geological disposal. The accelerator performance, target-blanket physics, chemical-processing requirements, and overall systems engineering are closely coupled in determining the economic incentives for the Accelerator Transmutation of Waste (ATW). Preliminary estimates of and insight into the economics of a net-power-producing ATW are provided by a simplified (analytic) cost-based systems model. Even for large-capacity systems, the accelerator dominates the economics and technology for the ATW cases examined. Since the accelerator represents an important (-50%) add-on cost to an ATW-based power plant, reducing the accelerator requirement by increasing the blanket neutron multiplication, increasing the thermal-conversion efficiency, and reducing neutron leakage and parasitic absorption in the target-blanket assembly are main avenues for improving the economic prospects of an ATW that would be fuelled with low-reactivity, actinide "waste" generated by light-water fission reactors (LWRs). This route to improved systems has strong implications for the thermalhydraulic, neutronic, and chemical-processing designs of the ATW.

I. Introduction

The coupled interactions between accelerator and target/blanket physics, overall system engineering, and the economics of unique combinations of power production and waste transmutation require a detailed systems model to provide guidance in evaluating optimal design directions. In addition to evaluating technology and economic tradeoffs that are intrinsic to the ATW, a range of non-linear and interactive scalings, as well as interfaces with front-end and back-end process streams, require quantitative evaluation. The ATW Systems Code (ATWSC) is being developed to provide a structure within which to project systematically on a cost basis the overall system performance for a wide range of design inputs and constraints. The non-linearities and the multiplicity of interdependent systems that characterize ATWSC, however, canobscure the root drivers of fundamental tradeoffs, despite the basic simplicity of individual physics/engineering scaling and cost estimating relationships presently in use.

At the risk of suggesting optimized costs that are even more approximate than those projected by **ATWSC,** a relatively transparent analytical systems model of the ATW is derived and parametrically evaluated. The main goal of this exercise is to illustrate analytically the main economic tradeoffs and cost drivers associated with a net-power-producing ATW that is fueled with low-reactivity actinide “waste” from commercial fission reactors. The simplicity of the analytic systems model is achieved at the expense of (relative to ATWSC) lumped systems parameters and unit costs, loss of secondary size scaling, and bottom-line costs that may not be complete; the general economic sensitivities to key subsystem performance, however, remain valid. Table I summarizes and defines the nearly three dozen parameters need to characterize this simplified ATW systems model, with approximately half being specified and the remainder being derived.

II. Model

Figure 1 depicts the essential elements of the simplified ATW systems model. The ac electrical power P_{EA} is converted with efficiency η_{DC} to dc power, which in turn is converted to rf power P_{RF} with efficiency η_{RF}. For purposes of simplicity and without loss in accuracy, P_{EA} is taken here as the only component of the plant recirculating power. Neglecting the ion-beam injection power, the radio-frequency power P_{RF} is delivered to the main section of the linear accelerator (the coupled-cavity linac, CCL) and divides between the beam, $P_B = I_B E_B$, and the rf cavity, $(G^2/R_s)l$, where all quantities are defined in Table I. The accelerator length required to create a proton beam of energy E_B is $l = E_B/G \cos \phi$, where ϕ is the phase angle between the accelerating particle bunch and the rf voltage. Hence, with $P_{RF} = P_B + (G^2/R_s)l$ and $P_{EA} = P_{RF}/\eta_{DC}/\eta_{RF}$, the overall accelerator efficiency is given by

$$\eta_A = \frac{\eta_{DC}\eta_{RF}}{1 + I^*/I_B} , \qquad (1)$$

where $I^* = G/R_s \cos \phi$ is a constant having the units of current and when multiplied by E_B gives the part of P_{RF} that is dissipated as low-grade heat in the walls of the rf cavity.

The proton beam of current I_B and final energy E_B impinges onto a spallation target that delivers Y neutrons to the blanket per incident proton onto the target. To a high level of accuracy, the dependence of neutron yield per incident proton on proton beam energy for a bare target is represented by the off-set linear function depicted schematically on Fig. 2 and approximated algebraically by the following expression:

$$E_B/Y = \frac{y}{1 - E_o/E_B} \quad , \qquad (2)$$

where the fitting constants y(MeV/n) and E_o(MeV) for a bare lead target [1] are given in Table I. It should be noted that these computational results pertain to a relatively unoptimized target, with design-specific material (e.g. Be multiplier) and geometry (length *versus* radius) target choices possibly leading to 5-10% increases in Y.

The neutron source strength $I_n = YI_B/e$, where e = 1.603 $\times 10^{-19}$ C, is assumed to enter without loss (leakage or parasitic absorption) a fission-multiplying blanket with a multiplication of M_n and an average neutron release per fission equal to v. Given E_F(MeV/fission), the fission power deposited in the blanket is given by

$$P_F = Y\, P_B(E_F/E_B)(M_n/\nu)\,. \qquad (3)$$

The assumption is made that the proton beam power, PB, along with PF, is capture by a high-temperature coolant and converted to electrical power, P_{ET}, with an efficiency η_{TH}, as is depicted on Fig. 1. After subtracting the power required to drive the accelerator, P_{EA}, from the gross electrical power, P_{ET}, the power $P_E = P_{ET} - P_{EA}$ is available as a source of revenue. The ratio $\varepsilon = P_{EA}/P_{ET}$ is defined as the recirculating power fraction. Other recirculating or "housekeeping" power requirements can be identified (typically 3-5% of P_{ET}), but, for the purpose of this analytic model, these are assumed to be small compared to the accelerator requirements.

The ATW is assumed to be fueled with the actinides rejected as waste from LWR client reactors. Each 1,000-MWe LWR generates actinides at a rate of -1,360 mole/yr, or R_{ACT} = 326 kg/yr/LWR, which translates into a specific power of β = 868 MWt/LWR Hence, expressing $P_F = \beta$ N in terms of N 1,000-MWe client LWRS reactor being served, the combination of Eqs (2) and (3) leads to the following relationship between P_B and EB:

$$P_B = \frac{N\,\beta\, y}{(M_n/\nu)E_F}\,\frac{E_B}{(E_B - E_o)} \qquad (4)$$

These expressions relate the strength of the accelerator neutron source required to burn the actinides from N 1,000-MWe LWRS, with the degree to which the neutron requirements of certain long-lived fissions products are satisfied being dictated largely by the choice of M_n, as is shown later. The specific cases being considered here assume only actinide waste from LWRS is burned; other more optimistic approaches propose increased reactivity and M_n by burning fissile fuel bred *in situ*, along with the prospects of enhanced economics through larger power production and reduced accelerator requirements.

In estimating the total direct cost, TDC(M$), five cost categories are introduced and evaluated on the basis of five constant unit cost factors. As noted above, the more detailed ATWSC evaluates a broader range of less-integrated cost categories with cost estimating relationship(CERs) that are functions of the respective capacities (e.g. W, kg/yr, I/m, $1/m^2$, $1/m^3$, etc). The five costs and the respective (constant) unit costs are summarized as follows:

* accelerator structure: $c_{CCL} l = c_{CCL} \dfrac{E_B}{G \cos\phi}$ (5)

* rf power: $c_{RF} P_{RF} = c_{RF}(P_B + I^* E_B)$ (6)

* thermal power handling: $c_{TH} P_{TH} = c_{TH}(P_F + P_B)$ (7)

* electrical plant equipment: $c_E P_{ET} = c_E \eta_{TH}(P_F + P_B)$ (8)

* chemical plant equipment: $C_{CPE} R_{ACT} = C_{CPE} \beta' N$, (9)

where β' = 326 kg(HM)/yr/LWR. Summing these direct costs and using Eqs. (3) and (4) to eliminate P_F gives the following expression for the total direct cost, TDC(M$):

$$TDC = a_1 P_B + a_2 E_B + a_3 \quad , \qquad (10)$$

where

$$a_1 = c_{RF} + c_{TH} + \eta_{TH} c_E \qquad (10a)$$

$$a_2 = \frac{c_{CCL}}{G \cos\phi} + \frac{G}{R_s \cos\phi} c_{RF} \qquad (10b)$$

$$a_3 = \beta N(c_{TH} + \eta_{TH} C_E) + c_{CPE} \beta' N . \qquad (10C)$$

Equation (4) relates P_B to E_B for a give level of LWR support, N. Two interesting observations can be made from the simple scaling of direct cost given by Eq. (10). Firstly, for given values of the (constant) unit costs, beam power, and beam energy, the economic tradeoff between accelerator power and accelerator structure gives a value of "real-estate" gradient, G, where TDC is minimized; increasing values of G for fixed beam parameters reduce the cost of accelerator structure [Eq. (5)], but the power dissipated in the cavity [Eq. (1)] is increased. Differentiation of TDC with respect to G for fixed values of I_B and E_B and setting the result to zero gives this cost-optimum value of the accelerator real-estate gradient.

$$G_{opt} = [(c_{CCL}/c_{RF})R_s]^{1/2} \quad . \tag{11}$$

Generally, high rf unit cost favor lower values of G and longer accelerating structures, and visa versa for high values of c_{CCL}. Secondly, TDC shows a minimum as a function of E_B for given values of unit costs and real-estate gradient, again reflecting an economic balance between accelerator structural and rf-power costs. Differentiation of TDC with respect to EB, using the optimum value G_{opt}, and solving for the cost-optimum proton beam energy gives

$$(E_B - E_o)^2 = \frac{\beta y N}{(M_n/\nu)(E_F/E_o)} \; \frac{c_{RF} + c_{TH} + \eta_{TH} c_E}{2 \; c_{RF} \; I^*} \quad " \tag{12}$$

Equation (12) in a single expression illustrates the functional dependence of cost-optimum beam characteristics on the main unit costs, the blanket multiplication, the system capacity (i.e., N), and the target yield characteristics (i.e., y and E_o).

Minimization of only accelerator-related costs will give a somewhat different beam-energy optimum. In addition to the cost of accelerator structure and rf power, those parts of the thermal and electrical balance-of-plant systems needed to generate the electrical power recirculated to the accelerator must also be included as part of the total accelerator cost. This direct cost associated with the accelerator is given by

$$TDC_{ACC} = c_{CCL} \, l + c_{RF} P_{RF} + (c_E + c_{TH}/\eta_{TH}) P_{EA} = a_4 E_B + a_5 P_B \tag{13}$$

$$a_4 = \frac{c_{CCL}}{G \cos \phi} + \frac{G \quad c^*}{R_s \cos \phi} \tag{13a}$$

$$a_5 = c^* = c_{RF} + \frac{\eta_{TH} c_E + c_{TH}}{\eta_{DC} \eta_{RF} \eta_{TH}} \quad " \tag{13b}$$

This direct cost associated only with the accelerator shows a minimum for the following beam energy:

$$(E_B - E_o)^2 = \frac{\beta y N}{(M_n/\nu)(E_F/E_o)} \; \frac{1}{I^*(1 + c_{RF}/c^*)} \quad " \tag{14}$$

It should be noted that constraints related to beam quality and structural heating impose upper limits on IB, and, depending on the magnitudes of N or M_n, the cost-optimized values suggested by Eqs. (12) or (14) may not be attainable.

Since the main product and source of revenue for the ATW being considered here is electrical energy, the cost of electricity, COE(mill/kWeh), represents a relevant cost to be optimized. Multiplying TDC by a contingency factor, CONT, and multiplying that result by an indirect-cost factor, IDC, gives the total cost, TC = CONT x IND x TDC. When TC is multiplied by an annual fixed-charge ratio, FCR(1/yr), and divided by the annual energy production, $p_f P_E$, where p_f is the annual plant availability factor, an approximate expression for COE results. After re-arranging, the cost of electricity is given by

$$\mathrm{COE} = \frac{\mathrm{FCR} \times \mathrm{CONT} \times \mathrm{IDC} \times 10^6}{8{,}760\, p_f} \frac{a_1 P_B + a_2 E_B + a_3}{-b_1 P_B + b_2 E_B + b_3} \tag{15}$$

where

$$b_1 = \frac{1}{\eta_{DC}\eta_{RF}} - \eta_{TH} \tag{15a}$$

$$b_2 = \frac{I^*}{\eta_{DC}\eta_{RF}} \tag{15b}$$

$$b_3 = \eta_{TH}\, \beta\, N \ . \tag{15c}$$

Equation (15) also predicts a value of E_B where COE is a minimum, but the resulting expression for E_B is quartic; therefore, Eq. (15) is evaluated parametrically for the nominally fixed input summarized in Table I. It is re-emphasized that Eq. (15) for COE is approximate, with values for FCR, CONT, and IDC being chosen to reflect the nuclear-standard, present-worth cost basis[3] used in the more detailed ATWSC. Also, this expression for COE does not reflect the incremental cost associated with fission-product waste disposal *versus* burnup; in a strict accounting sense, any increment in COE above the existing rate (e.g., the rate charged by the client LWRs) would be spread over the client reactors as an incremental fuel-cycle charge.

Coupling of the target/blanket neutron economy is made in this simplified model only through the parameters M_n and ν, which are related to the average capture-to-fission ratio for the actinide "lump" α, and the ratio of all absorption occurring in the actinide, f (i.e., and effective product of thermal utilization factor and resonance escape probability), as follows:

$$k_{eff} = \frac{M_n}{1 + M_n} = \frac{\nu}{1 + \alpha} f P_{NL} \ , \tag{16}$$

where k_{eff} is the neutron multiplication constant and P_{NL} is a global neutron non-leakage probability. For the blanket parameters listed in Table I, which correspond roughly to an equilibrium actinide lump under irradiation in a D_2O moderated blanket[4], the effective thermal utilization factor amounts to f = 0.91 for M_n = 10, which indicates that without leakage the number of non-actinide absorption per source neutron is $(M_n/\nu)(1 - f)$ - 0.31. Since the ratio of long-lived fission product production to actinide lump production from an LWR[2] amounts to -317/1363 = 0.23, a margin of 0.31/0.23 = 1.35 exists for dealing with internally generated fission products and structural/target parasitic absorption. Generally, neutron demands beyond this level will require a larger accelerator capacity for a given actinide burn rate, thereby increasing the COE; the use of capacity-scaled CERS, however, as is done in ATWSC, will lead to reductions in the predicted COEs at higher capacity, thereby having a countervening influence. Nevertheless, the nuclear performance assumed in this analysis is simplified and optimistic; a neutronically, thermalhydraulically, and chemically self-consistent target-blanket design will increase "non-productive" neutron losses to structure and fission products, thereby driving down the value off and increasing cost for a given production goal. As noted previously, the burning of fissile fuel bred *in situ* will have a strong impact on the overall neutron economy, the ability to transmute increased levels of fission-product waste, and the overall system economics through increased power production and reduced accelerator requirements. Resolution of these complex techno-economic tradeoffs is a key component of ongoing ATW design activities.

III. RESULTS

The sample results presented herein are intended primarily to demonstrate general tradeoffs rather than to espouse optimal ATW design points *per se.* As a minimum, the level of detail being developed into ATWSC is required before design-specific projections can be made. Figure 3 gives the dependence of COE and TC on E_B for N = 6. The cost minima described above analytically are shown, with the optimization based on COE being made more pronounced through the inverse dependence on net-electric power. Shown also on this figure is the dependence of beam current, with minimum-COE systems requiring $I_B \geq$ 300 mA. The cost impact associated with constraining I_B below the minimum-COE point is readily seen from this figure; decreasing I_B from the ~300-mA optimum to 200 mA is accompanied by a - 3 mill/kWeh cost penalty for this N = 6 system. Also shown on Fig. 3 is the fraction f_{ACC} of TDC associated with the accelerator, which for the minimum-COE design amounts to 49% of the total direct cost. The net-electric power for this N = 6 case is 1,100 MWe, and the recirculating power fraction is ε = 0.32. Generally the economic burden of the accelerator for this M_n = 10 system is significant.

The N = 6 sample case reported in Fig. 3 has been repeated for a range of 1,000-MWe LWR support capacities, with the dependence of COE and TC on E_B and N being shown in Fig. 4. In addition to giving the locus of minimum-COE points as N is varied, Fig. 4A inscribes lines of constant beam current, again indicating relatively small cost penalties if I_B can be maintained above a few 100s of milliamperes. Also shown is a point of diminishing returns in reduced COE as overall capacity ($N \propto P_E$) is increased. This point of diminishing returns is extended somewhat if capacity-dependent CERS (i.e., $c_{TH} \sim 1/P^n_{TH}$) are used.

The four frames in Fig. 5 give explicitly the dependence of minimum-COE system parameters on the number of 1,000-MWe LWRS serviced: COE, TC, and ε on Fig. 5A, E_B, I_B, and P_B on Fig. 5B; beam, accelerator, thermal, total-electric, and net-electric powers on Fig. 5C; and the division of accelerator-related costs on Fig. 5D. Even for these cost-optimized systems, the dominance of the accelerator ($f_{ACC} \simeq 0.5$) and the high recirculating powers ($\varepsilon \gtrsim 0.30$) generally limit the attractiveness of the system. Interestingly, the dominant costs associated with the accelerator are for rf power supplies and the incremental BOP need to generate the required recirculating power (i.e., f_{RF} and f_{POW} in Fig. 5D).

At the level of the present analysis, increased blanket multiplication, M_n, and thermal-to-electric conversion efficiency, η_{TH}, impact strongly the projected COE values by reducing the economic impact of the accelerator through reduced accelerator capacity and recirculating power (e.g., reduced BOP). The strong influence of M_n and η_{TH} on COE is illustrated in Fig. 6, which for the $\eta_{TH} = 0.3$ base case gives lines of constant net-electric power, P_E.

IV. CONCLUSIONS

A simplified analytic, cost-based systems model has been developed and evaluated for a net-power-generating ATW that burns long-lived fission products and actinides from N light-water fission reactors. Even for large-capacity systems, the accelerator is predicted to dominate the economics and technology for the base-case parameters assumed (Table I). The simplified cost scaling relationships, while not reflecting economy-of-scale benefits, are considered optimistic, particularly for the accelerator components. Similarly, the single-parameter neutronics assumed may also prove to be optimistic when the non-productive absorption of neutrons in structure and fission products are taken into account; an important variable in this regard is the technology and economics of the chemical processing required to hold parasitic absorption to acceptable levels for a given overall plant decontamination factor. At the level of the present analysis, however, reducing the accelerator requirement by increasing the blanket neutron multiplication, M_n, as well as increasing the thermal-to-electric conversion efficiency, η_{TH}, are main avenues for improving the economic prospects of this concept; this route to improved systems has important implications for the thermalh ydraulic, neutronics, and chemical-processing designs of the ATW target-blanket assembly, as well as the goal (e.g., current limitations) of the accelerator neutron source for high-M_n blankets.

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3. J. G. Delene and C. R. Hudson II, "Cost Estimate Guidelines for Advanced Nuclear Power Technologies," Oak Ridge National Laboratory report ORNIYI'N-1OO7VR2 (March 1990).

4. J. Sapir, W. Sailor and J. W. Davidson, personal communication, Los Alamos National Laboratory, (January 1992).

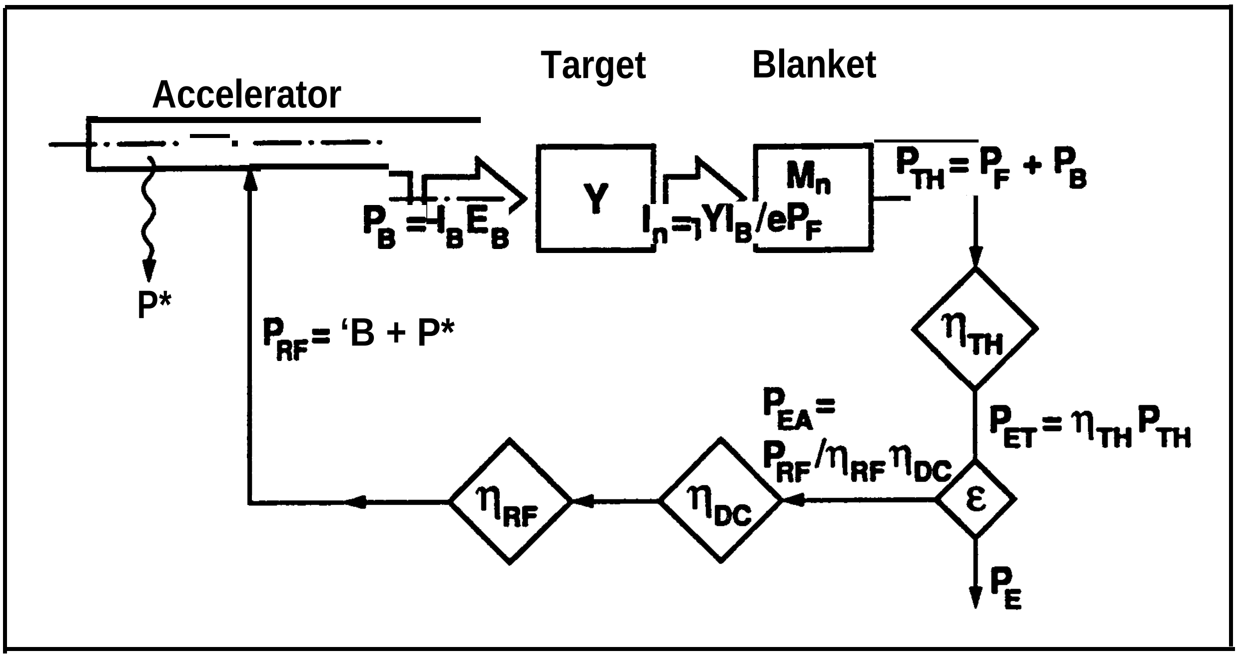


Figure 1. Power flows for analytic ATW systems model.

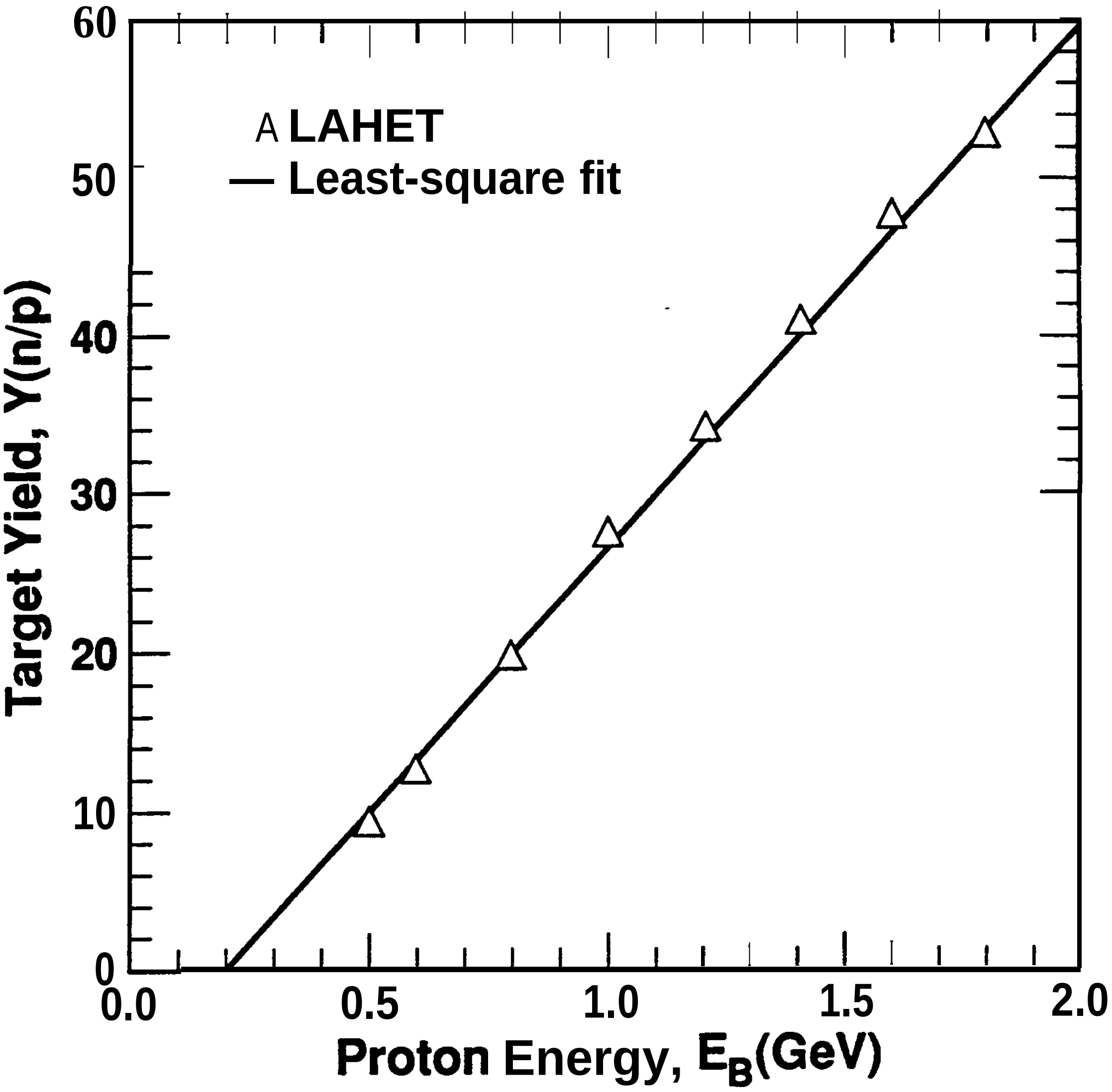


Figure 2. Neutron yields from a bare lead target[2].

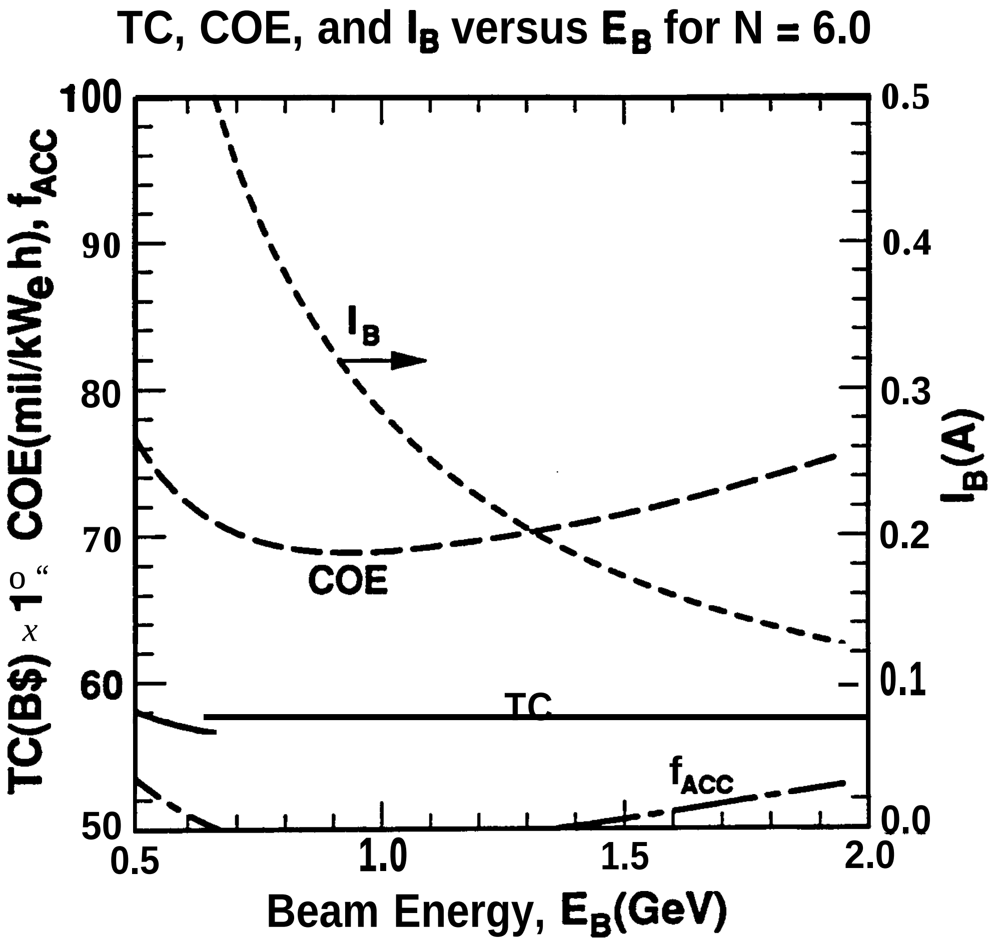


Figure 3. Plot of Eqs. (10) and (15) for TC = CONT x IDC x TDC and COE for N = 6; also shown are the required beam current, I_B, and the fraction $f_{ACC} = TDC_{ACC}/TDC$ [Eq. (13)] of the total cost devoted to the accelerator.

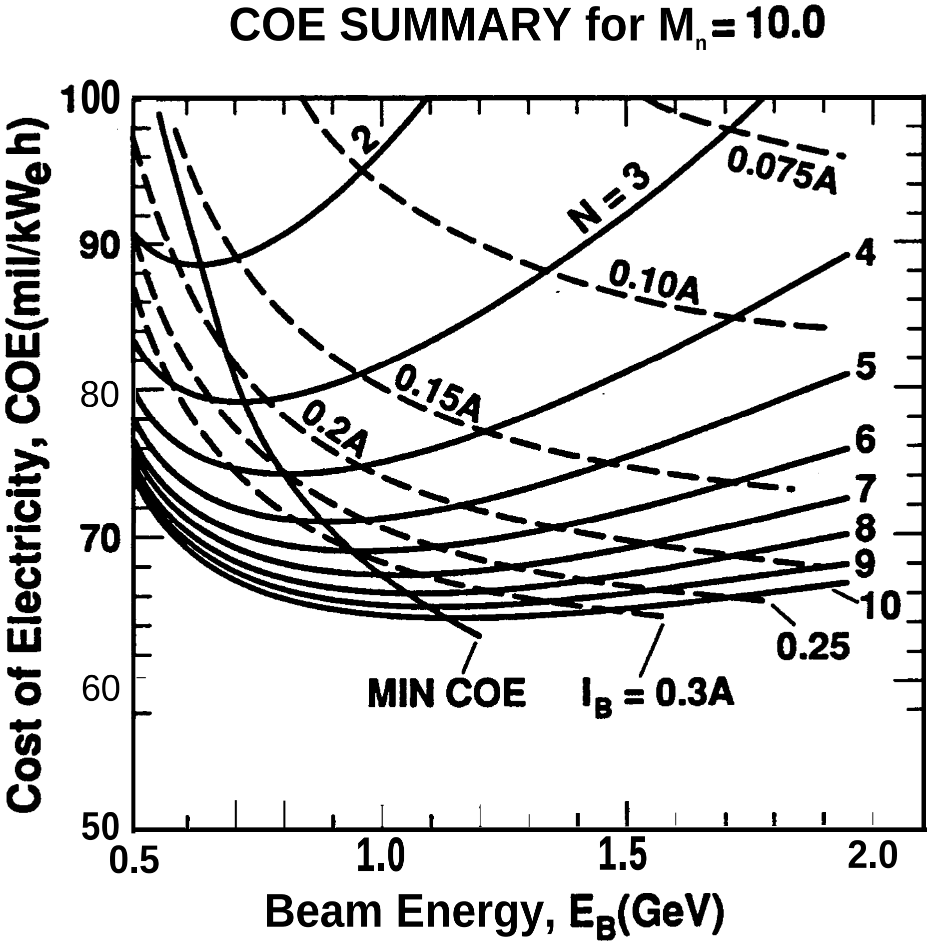


Figure 4. Dependence of COE (a) and TC (b) on beam energy, EB, and the number of 1,000-MWe LWRS being served, N, showing the impact of constrained beam current, IB, on COE.

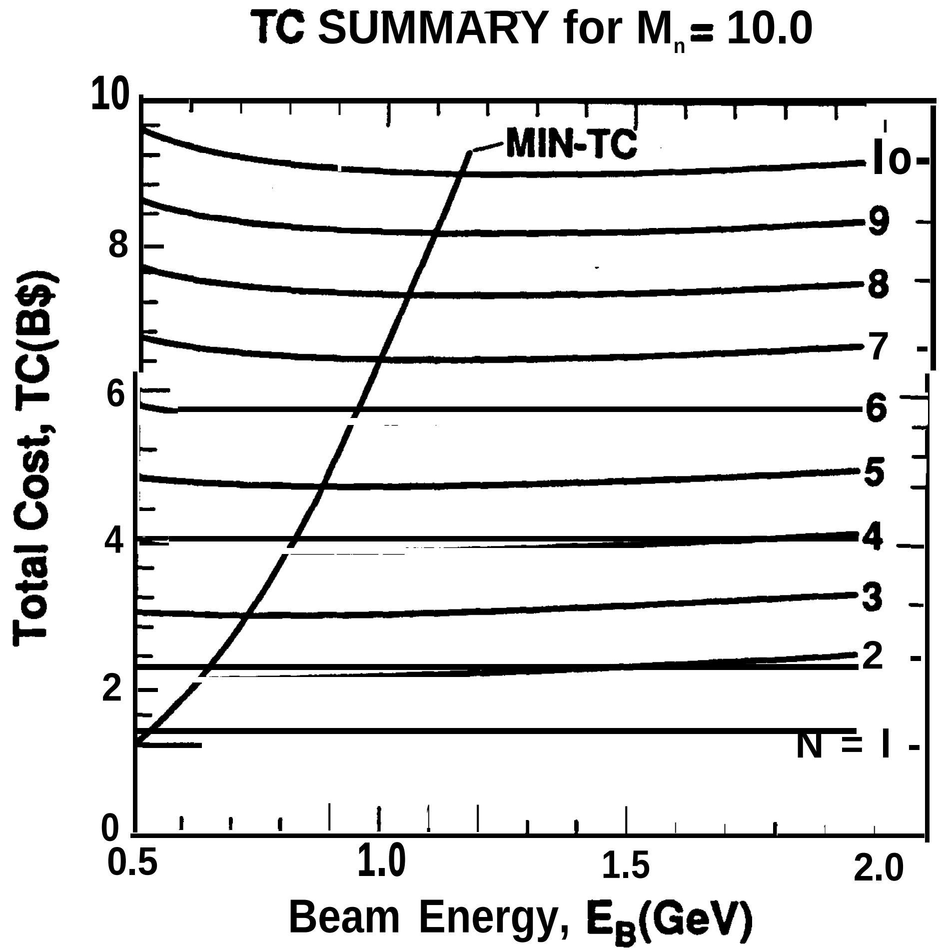

TC SUMMARY for M_n = 10.0
MIN-TC
Total Cost, TC(B$)
Beam Energy, E_B(GeV)
10
8
6
4
2
0
0.5
1.0
1.5
2.0
Io
9
8
7
6
5
4
3
2
N = I

Figure 4b.

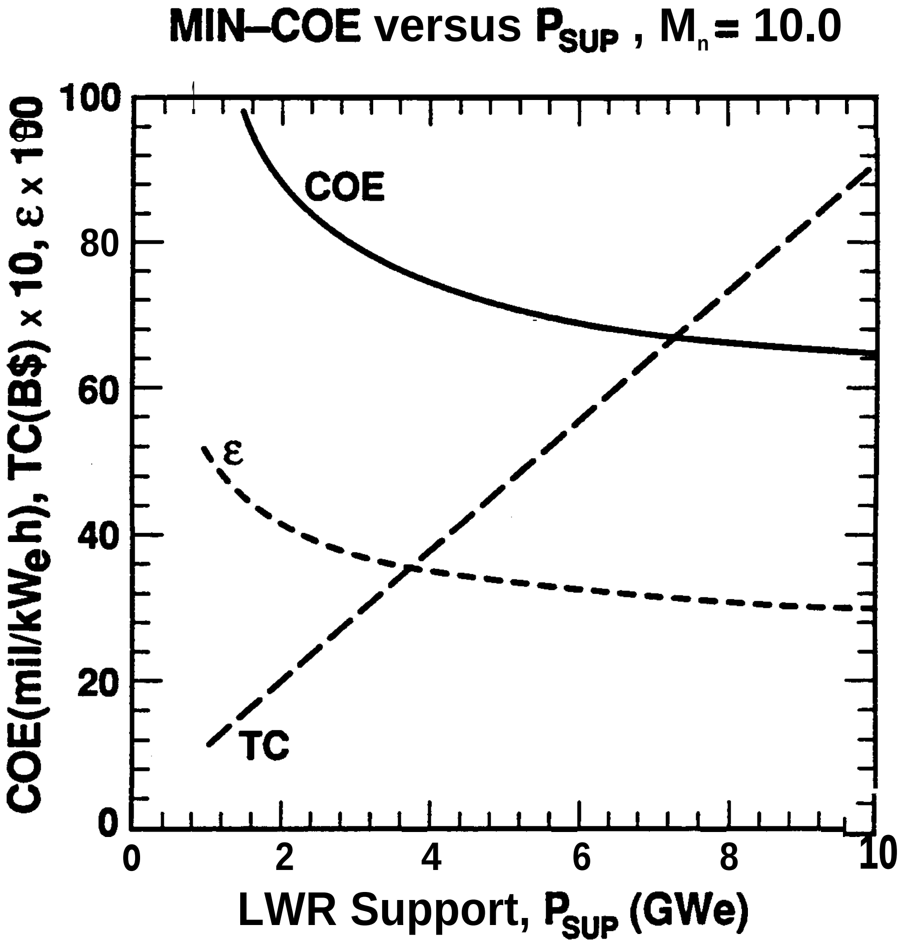


Figure 5. Dependence of key system costs (a) and parameters [accelerator (b), powers (c), and cost allocations (d)] on the number of 1,000-MWe LWRS served, N, for minimum-COE conditions.

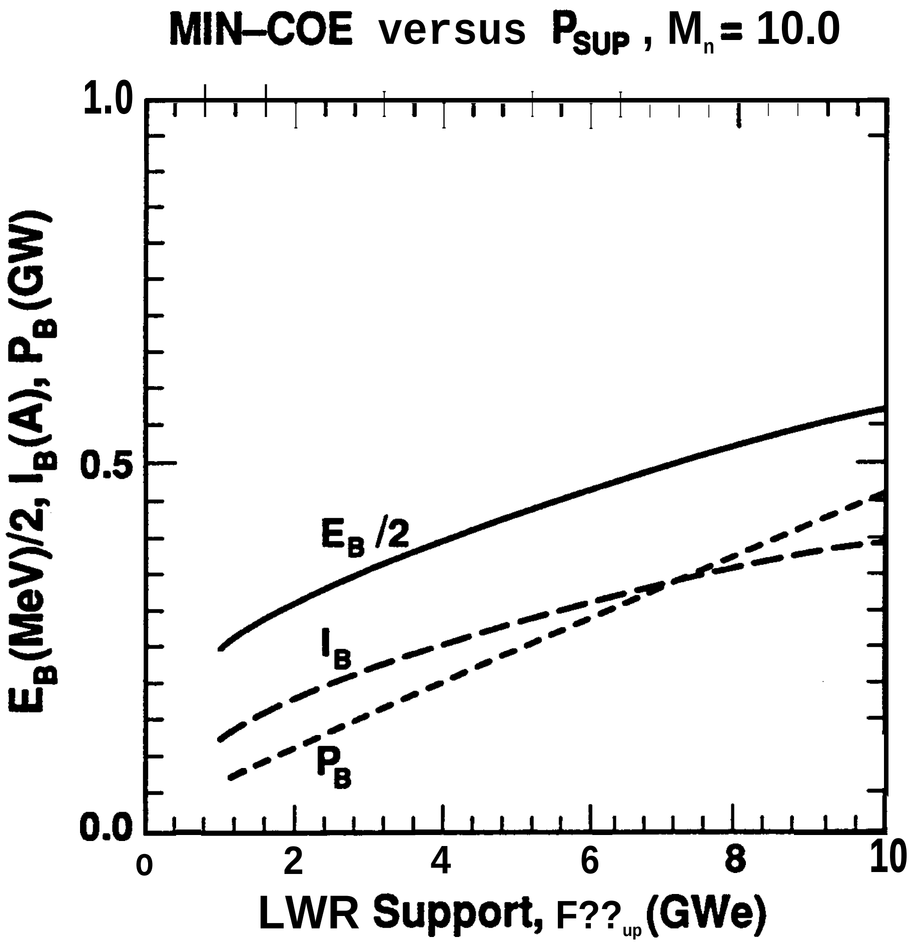
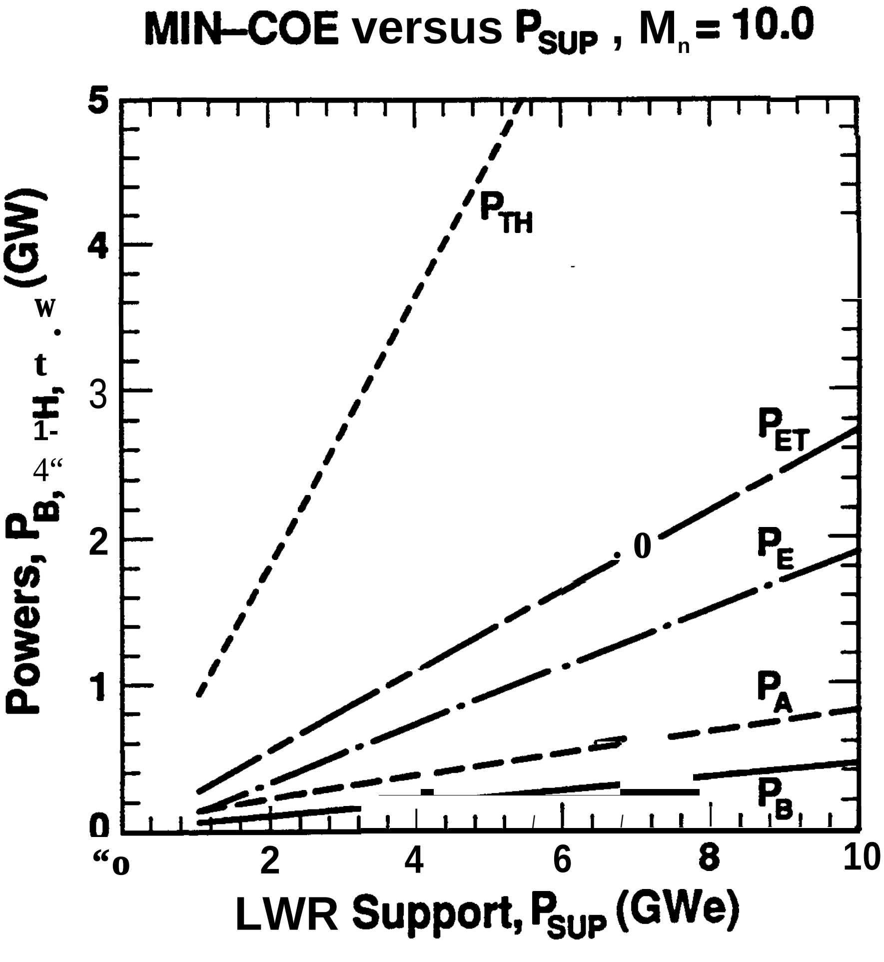

MIN–COE versus PSUP , Mn = 10.0
1.0
0.5
0.0
EB(MeV)/2, IB(A), PB(GW)
EB /2
IB
PB
0
2
4
6
8
10
LWR Support, F??up (GWe)

Figure 5b.



MIN–COE versus P_{SUP} , $M_n = 10.0$
Powers, P_B, P_{TH}, ... (GW)
LWR Support, P_{SUP} (GWe)
P_{TH}
P_{ET}
P_E
P_A
P_B
0
1
2
3
4
5
2
4
6
8
10

Figure 5c.

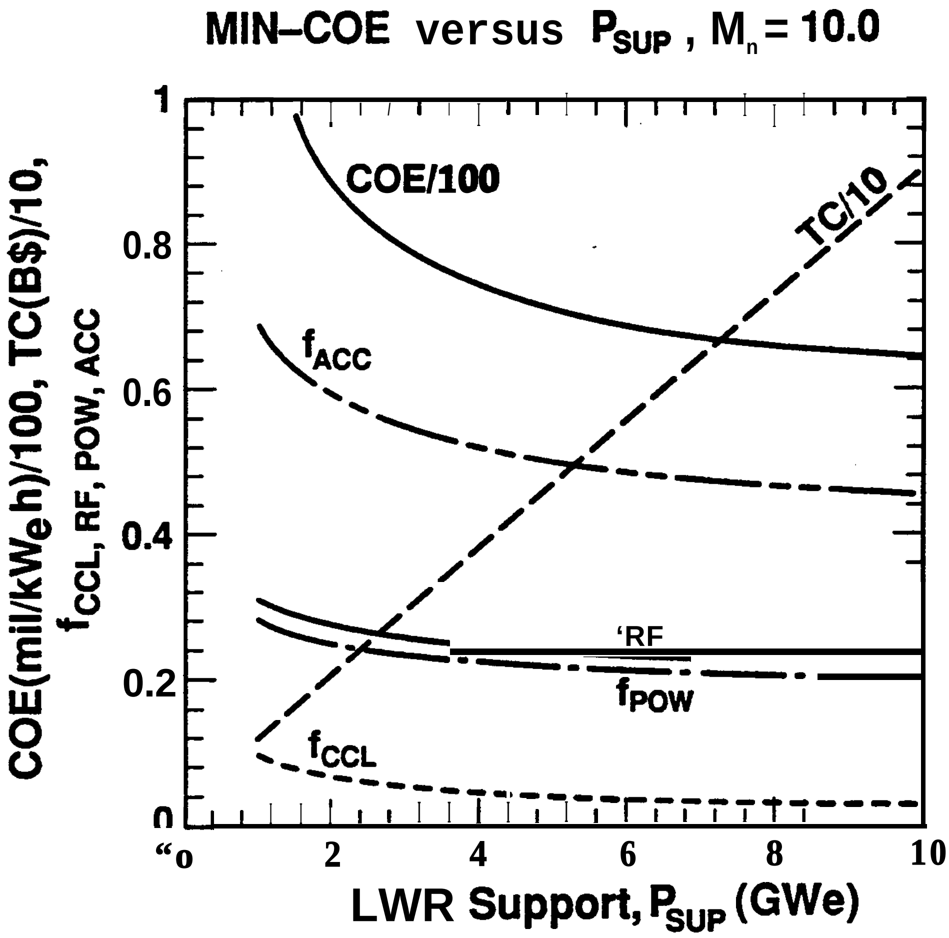

MIN–COE versus P_{SUP} , M_n = 10.0
COE(mil/kWeh)/100, TC(B$)/10,
$f_{CCL, RF, POW, ACC}$
COE/100
TC/10
f_{ACC}
'RF
f_{POW}
f_{CCL}
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
LWR Support, P_{SUP} (GWe)

Figure 5d.

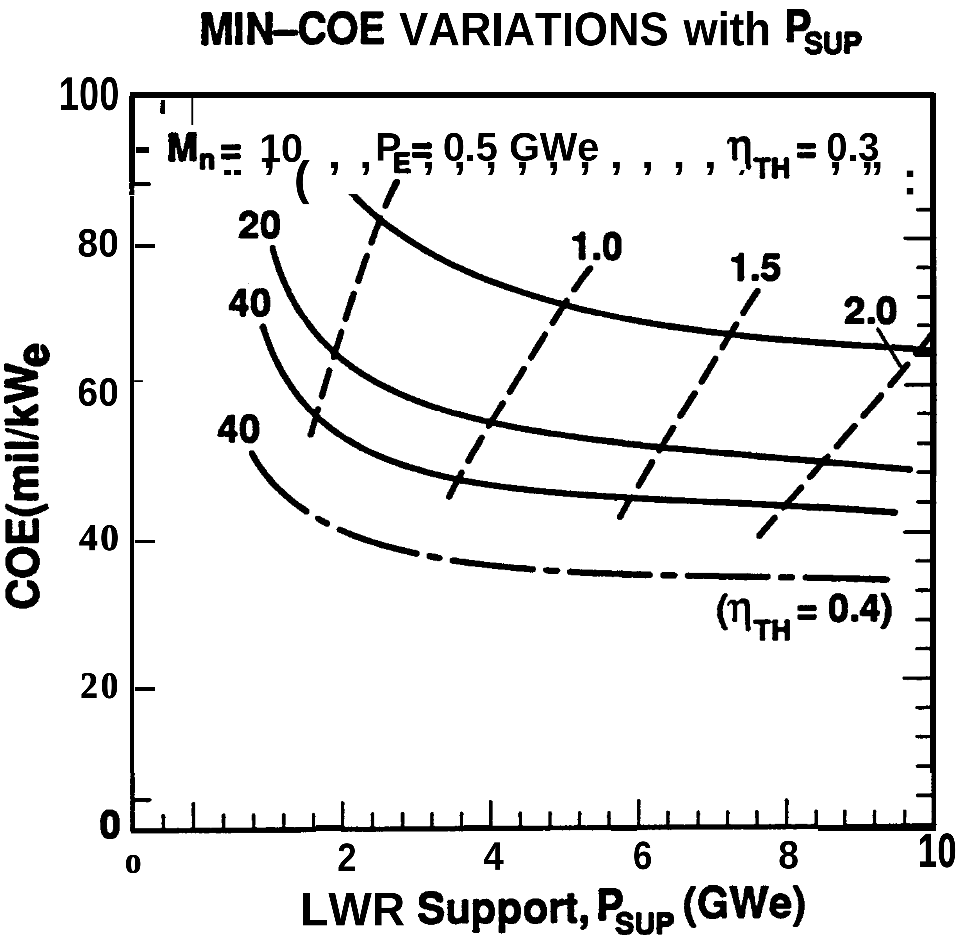


Figure 6. Dependence of COE on the number of 1,000-MWe LWRS served, N, blanket multiplication, M_n, and thermal conversion efficiency, η_{TH}.

Table I. Parameter Definitions and Values for Analytic ATW Systems Model

Parameter	Value
Costing/Economics	
thermal power systems, c_{TH}($/W)	0.20
electrical power systems, c_E($/W)	0.50
accelerator structure, c_A(M$/m)	0.10
radio-frequency power, c_{RF}($/W)	2.0
chemical plant equipment, c_{CPE}(M$/kg/yr)	0.10
interest-during-construction factor, IDC/TDC + 1	1.60
contingency factor, CONT/(IDC+TDC) + 1	1.20
fixed charge rate, FCR(1/yr)	0.10
cost of electricity, COE(mill/kWeh)	[(Eq. (15)]
total direct cost, TDC(M$)	[(Eq. (10)]
total cost, TC(M$)	IDC x CONT x TDC
Accelerator	
CCL length, l(m)	$E_B/G \cos\phi$
cost-optimum ccl gradient, $G_{opt}(MV/m) = [(c_{CCL}/c_{RF})R_s]^{1/2}$	1.09
CCL shunt resistance, R_s(Mohm/m)	24.0
cosine of particle-to-voltage phase angle, $\cos\phi$	0.77
beam current, I_B(A)	--
beam energy, E_B(MeV)	.-
beam current parameter, $I_B^* = G/(R_s \cos\phi)$ (A)	0.054
beam power, P_B	$I_B E_B$
cavity power loss, P_Ω	$I^* E_B$
radio-frequency power, P_{RF}	$P_\Omega + P_B$
overall accelerator efficiency, η_A	P_B/P_{EA}
Target/Blanket	
neutron/proton yield, Y(n/p)	[Eq. (2)]
target yield fitting parameters	
• y(MeV/n)	30.1
• E_o(MeV)	201.4
blanket neutron multiplication, M_n	10.0
actinide fission neutron yield, ν(n/fission)	2.9
actinide capture-to-fission ratio, α	1.9
number of 1,000-MWe LWRS supported, N	. .
waste burnup rates[2]	
• actinide, R_{ACT}(mole/yr/LWR)	1,363.
• fission product, R_{FP}(mole/yr/LWR)	317.
actinide energy content, β(MWt/LWR)	868.
chemical processing rate per LWR, β'[kg(HM)/yr/LWR]	326.
nominal actinide atomic mass, A	240.
fission power, P_F	868
N	

fission energy release, E_f(MeV/fission)	200.
Plant	
plant availability, p_f	0.75
thermal-to-electric conversion efficiency η_{TH}	0.30
ac-to-dc conversion efficiency, η_{DC}	0.86
dc-to-rf conversion efficiency, η_{RF}	0.75
thermal power converted to electricity, P_{TH}(MW)	$P_B + P_F$
total electrical power, P_{ET}(MW)	--
net electrical power, P_E(MW)	--
electrical power to accelerator, P_{EA}(MW)	P_B/η_A
recirculating power fraction, $\varepsilon = P_{EA}/P_{ET}$	--