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GENEROMAK
Fusion Physics, Engineering and Costing Model

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ABSTRACT

A generic fusion physics, engineering and economics model (Generomak) was developed as a means of performing consistent analysis of the economic viability of alternative magnetic fusion reactors. The original Generomak model developed at Oak Ridge by Sheffield was expanded for the analyses of the Senior Committee on Environmental Safety and Economics of Magnetic Fusion Energy (ESECOM). This report describes the Generomak code as used by ESECOM. The input data used for each of the ten ESECOM fusion plants and the Generomak code output for each case is given.

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1. INTRODUCTION

The ultimate viability of any fusion power option will depend to a large extent on its economics relative to other fusion power systems and to all available electric power producing options in general. It is important in analyses that the methods used in evaluating all concepts be consistent and should not prejudice the results. This should include both the economic evaluation models and the calculational model for the fusion system. These economic models should reflect accepted engineering economic treatments and utility procedures.

A generic fusion physics, engineering and costing model (Generomak) was developed by Sheffield and Dory as the analysis tool in the "Cost Assessment of a Generic Magnetic Fusion Reactor".[1,2] This model was adopted by the Senior Committee on Environmental, Safety and Economic Aspects of Magnetic Fusion Energy (ESECOM)[3] as a starting point for the fusion physics/economic characterization models used in their study. During the course of the ESECOM analyses refinements were made to the original Generomak procedures reported by Sheffield.[1,2] These refinements were principally in the areas of costing and economic methodology. ESECOM also had to deal with 10 different Fusion type/blanket concepts which were integrated into the overall model.

This report describes the Generomak code as used in the ESECOM analyses. Although the model is approximate and should not be used for detailed fusion reactor design calculations, it provides a self-consistent, quantitative intercomparison between alternatives and can provide a sense of the direction of the cost impacts of alternate actions. The reference fusion power plant model is for a vanadium structure, lithium coolant/breeder blanket (V-Li/TOK). The physics/engineering model and economics modeling will be described in detail for this design. The other designs as described in Table 1.1 will be discussed as they depart from the reference. The models are a product of the deliberations of

Table 1.1. Fusion plant models

V-Li/TOK	–	A "point of departure" fusion reactor in the tokamak configuration, with vanadium structure and liquid lithium (Li) as the coolant/breeder.
RAF-He/TOK	–	A helium-cooled variant of the "point of departure" tokamak, with reduced activation ferritic-steel (RAF) structure and Li_2O solid breeder.
RAF-LiPb/RFP	–	A high-power-density, reverse-field pinch (RFP) with RAF structure, self-cooled lithium-lead breeder, and water-cooled first wall and limiter.
V-Li/RFP	–	Another high-power-density RFP with a V/Li/Li blanket minimally modified from that of the "point of departure" tokamak.
SiC-He/TOK	–	A "low-activation" tokamak with silicon carbide (SiC) structure, helium coolant, and Li_2O breeder.
V-FLiBe/TOK	–	A "pool" type tokamak with vanadium structure and molten-salt (FLiBe) coolant/breeder.
V-MHD/TOK	–	An advanced-conversion variant of the point-of-departure tokamak with synchrotron-radiation enhanced magnetohydrodynamic (MHD) conversion.
V-DHe$_3$/TOK	–	An advanced-fuel fusion reactor based on the D-He$_3$ fuel cycle with direct conversion of microwave synchrotron radiation.
RAF-Li/HYB	–	A "baseline" fusion-fission hybrid tokamak with RAF structure, lithium coolant, beryllium neutron multiplication, and thorium metal as the fertile material.
SS-He/HYB	–	An "advanced technology" hybrid tokamak with stainless-steel structure, helium coolant, and molten-salt blanket (70LIF-12BeF_2-18ThF_2).

the ESECOM as a whole with specific contributions on the various models of B. Grant Logan, (LLNL) V-MHD/TOK and V-DHe3/TOK; Kenneth R. Schultz (G. A. Technologies, Inc.), RAF-He/TOK, SiC-He/TOK and V-FLiBe/TOK; David H. Berwald (Grumman Aerospace Corp.), RAF-Li/HYB and SS-He/HYB; and Robert A. Krakowski (LANL), RAF-LiPb/RFP and V-Li/RFP. Krakowski, Sheffield and Dory contributed to the plasma physics and engineering portions of the analysis procedures. Delene contributed to the economic methods and analysis procedures, and modified and extended the Generomak code into its present state.

Section 2 contains a description of the Fusion Physics and Engineering models. Section 3 describes the economic methodology and costing models. Section 4 discusses the basic data for the 10 ESECOM models, and Sect. 5 describes the operation of the Generomak code. The computer output for each of the 10 ESECOM cases is given in the Appendix of the report. Additional results may be found in the ESECOM report[3] and in a paper on the connections between physics and economics for the reference V-Li/TOK reactor.[4]

2. FUSION POWER PLANT MODEL

The Generomak model is for a steady-state reactor with deuterium-tritium (D-T) fuel and includes the components common to essentially all kinds of magnetic-fusion reactors. Although the model is approximate and should not be used for detailed design calculations, it provides a self-consistent, quantitative comparison between alternatives and can convey information about the direction and approximate magnitudes of the impacts of alternative design choices.

2.1 Base Case Model

The baseline Generomak reactor model represents an extrapolation of present physics and technology insofar as high beta (10%) and improved coil technology are assumed. The model itself, however, can be used to investigate alternative, more near-term assumptions.

Basically, the physics calculation involves an iteration on the toroidal field and plasma radius for fixed input values of power level, total plasma β, plasma aspect ratio, elongation of the toroidal cross section and maximum field in the coil. Plasma volume, neutron wall loading, and plasma current are then calculated using the converged values of plasma radius and toroidal field required to give a specified net-electric power output.

A detailed description of the Generomak model can be found elsewhere,[2] with the essential physics and engineering parameters for the base case listed in Tables 2.1 and 2.2. A further discussion of the Generomak procedures and results of sensitivity calculations can be found in Refs. 3 and 4. A schematic drawing of the radial build of the fusion power core (FPC) (i.e., plasma chamber, first wall, blanket, shield, coils, and structure) is given in Fig. 2.1. The elliptical plasma of elongation $\kappa = b/a$ is assumed to operate at the ballooning-mode stability limits given by the Lausanna group[5] and expressed as follows in terms of total beta, β, plasma current, I_ϕ, minor radius, a, and toroidal field at the plasma, B_ϕ.

Table 2.1. Generomak plasma parameters for Tokamak basecase

Aspect ratio, $A - R_T/a = 1/\varepsilon$	4.0
Elongation, $\kappa = b/a$	2.5
Safety factor, q_ψ	2.3
Total beta, $\beta = 0.04\ I_\phi/a\ B_\phi$	0.1
Plasma ion temperature, T_i (keV)	10
Ion electron beta ratio, τ_e/τ_i	1.0
Impurity (alpha-particle)/(electron) beta ratio	0.2
Plasma standoff, a_w/a	1.1
Current-drive efficiency,[a] I_ϕ/P_{cd} (A/W)	0.2
Plasma current, I_ϕ(MA)	$\frac{2.75\ B_\phi a\varepsilon\ (1 + \kappa^2)}{q_\psi\ (1 - \varepsilon^2)^2}$
Fraction of alpha-particle power to limiter	0.8

[a]Although the main approach used this efficiency, subsequent studies[3,4] on the Li-V/TOK examined the impact of fixing a "normalized" current-drive efficiency, $\gamma = n_e I_o R_T/P_{CD}$.

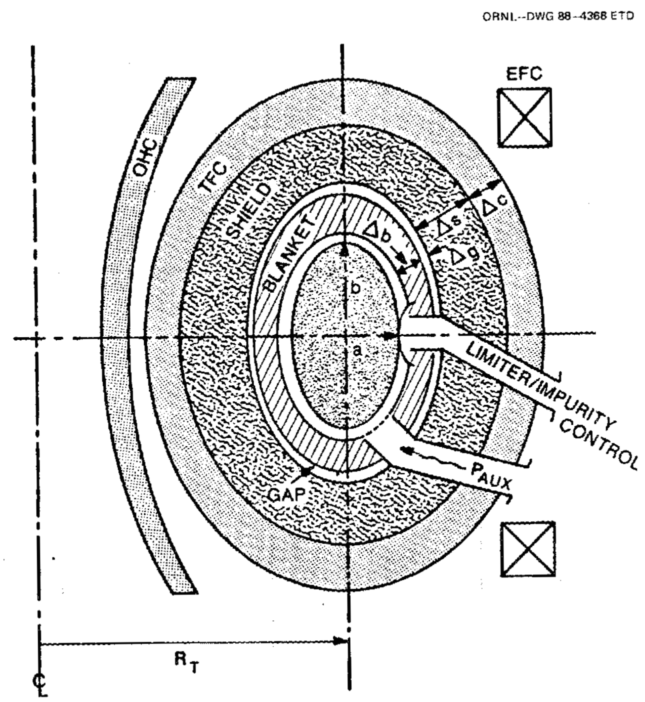

Fig. 2.1. Schematic diagram of Generomak fusion-power-core model.

Table 2.2. Generomak engineering parameters for tokamak basecase

Net electric power, P_E(MWe)	1,200
Thermal conversion efficiency, η_{TH}	0.404
Fusion-Power-Core dimensions	
◇ blanket thickness, Δb(m)	0.71
◇ blanket/shield gap, Δg(m)	0.10
◇ shield thickness, Δs(m)	0.83
Ratio of TFC[a] mass to masses of other coils (EFC,OHC)[a]	0.25
TFC current density, j_m(MA/m^2)	$\frac{(96 - 6B_m)}{1 + (B_m/12)^{1.5}}$
Availability	
◇ plant, p_f	0.65[b]
◇ auxiliary (current-drive) power	0.325
FPC "Smear" densities (tonne/m^3)	
◇ blanket	2.3
◇ shield	7.0
◇ coils	7.9
◇ structure	6.0
Structural volume fraction of coil	0.50
Fluence lifetime (MWyr/m^2)	
◇ limiter (heat)	10.0
◇ blanket and auxiliary heating (neutrons)	20.0
Recirculating power fraction to BOP[c]	0.06
Blanket neutron-energy gain, M_N	1.27
Number of blanket modules/section	6.0
Number of TFC sectors	20.0

[a]TFC is toroidal-field coil, EFC is equilibrium field coil, and OHC is ohmic-heating coil.

[b]If I_w(MW/m^2) is the neutron wall loading, and the radiation lifetime is $I_w\tau$(MWyr/m^2), then $p_f = 0.7534/[1+0.1034I_w/(I_w\tau)$ when $I_w/(I_w\tau) > 1.54\ yr^{-1}$. This expression is based on 90 days/year of unscheduled maintenance and 38 days per FPC changeout.

[c]The fraction of the gross electric power recirculated within the fusion power plant for all uses except current drive. The sum of the BOP power and current drive power, P_{CD}, gives the total recirculating power.

$$\beta \leq 0.04 I_\phi / a B_\phi \qquad (2.1)$$

The magnitude of the Troyon coefficient, $\beta a B_\phi / I_\phi = 0.04$, is optimistic since disruption-free operation of present-day tokamak designs requires this coefficient to be 0.035 or less. Expressed in terms of edge-plasma safety factor, $q_a \equiv B_\phi \varepsilon / B_\theta$, where $B_\theta = I_\phi / 5a$ is the poloidal field at the surface of a circularized plasma of radius a and $\varepsilon = 1/A = a/R_T$ is the inverse aspect ratio, the flux-defined safety factor is expressed as

$$q_\psi = 1.1 q_a \frac{(1 + \kappa^2)/2}{(1 - \varepsilon^2)^2} \, . \qquad (2.2)$$

The coefficient, C = 1.1, limits this fit of numerical results[6] to $\varepsilon \beta_\theta \leq 0.3$, with β_θ being the poloidal beta. The plasma current, I_ϕ, is assumed to be driven with lower-hybrid RF at a fixed efficiency, I_ϕ / P_{CD}, of 0.2 A/W delivered to the plasma. This assumption represents a significant advancement relative to values presently achieved for typical reactor parameters.

Pumped-limiter impurity control is assumed, and the relationship between current density in the superconducting coil, j_m(M A/m^2) and the field at the windings, B_m(T), is given by[2]

$$j_m(\mathrm{M\ A/m^2}) = \frac{96 - 6B_m}{1 + (B_m/12)^{1.5}} \qquad (2.3)$$

The relationship between B_ϕ and B_m is given by the following expression describing the radial fall-off of magnetic field:

$$\frac{B_\phi}{B_m} = \frac{R_T - (a_w + \Delta b + \Delta g + \Delta s + \Delta d)}{R_T} \, , \qquad (2.4)$$

where all dimensions are defined on Fig. 2.1. With the current density, j_m, and FPC geometry determined, the toroidal-field-coil (TFC) mass is computed; the poloidal-field-coil (PFC) mass is taken as 25% of the TFC mass for the tokamak cases.

In the base case (I_ϕ / P_{CD} fixed at 0.2 A/W) a plasma temperature of about 10 keV is assumed with an impurity beta taken as $\beta_Z = 0.2\, \beta_e$, where β_e is the electron beta taken equal to the ion beta, $\beta_e = \beta_i$. The ion beta then, in terms of the total beta, becomes[2]

$$\beta_i = 0.455\ \beta \tag{2.5}$$

The alpha power is given by

$$P_\alpha = 25.6\ \langle\beta_i\rangle^2\ B_o^4\ Rab\ (MW) \tag{2.6}$$

For the D-T fueled plant, the neutron power is $P_N = 4\ P_\alpha$. The fusion power is the sum of the alpha and neutron power

$$P_F = P_\alpha + P_N \tag{2.7}$$

The Generomak reactor power balance is described in Fig. 2.2, wherein the 14.1-MeV fusion-neutron power, P_N, is increased by the blanket energy multiplication, M_N, giving a total thermal power $P_t = M_N P_N + P_\alpha + P_{CD}$. Thirty percent of the alpha-particle, P_α, and current-drive powers delivered to the plasma, $(1-f_{CD})P_{CD}$, is assumed to appear as low-grade heat not usable by the thermal cycle. Of the total current-drive

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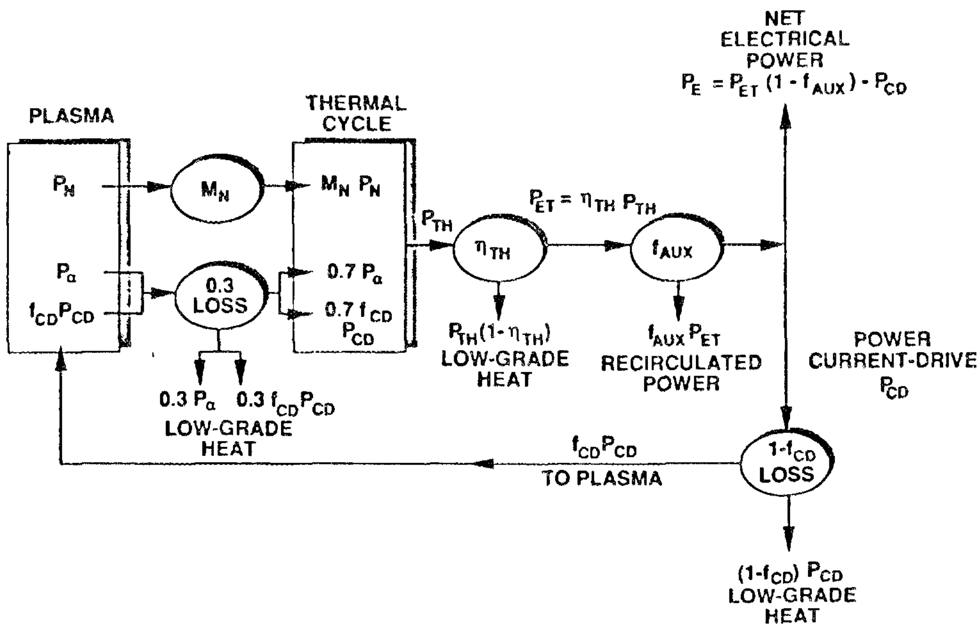

Fig. 2.2. Generomak power-plant energy balance.

power, the fraction, f_{CD}, is delivered to the plasma, the remainder also being lost as low-grade heat. For all cases considered by ESECOM, F_{CD} = 1. The total thermal power available, therefore, becomes

$$P_{TH} = M_N P_N + 0.7(P_\alpha + f_{CD} P_{CD}) , \tag{2.8}$$

The "available" thermal power is converted to the total electrical power, $P_{ET} = \eta_{TH} P_{TH}$, with an efficiency η_{TH}. Once converted to electrical power, the fraction $f_{AUX} \simeq 0.06$ of P_{ET} is recycled along with P_{CD} back to the power plant, giving a net-electric power for sale equal to

$$P_e = P_{ET}(1 - f_{AUX}) - P_{CD} . \tag{2.9}$$

The thermal efficiency used in the ESECOM analyses was determined by the blanket (i.e., primary loop) inlet and outlet temperatures and was taken as 75% of the ideal thermal efficiency, η_I, for a constant-pressure thermal transfer process. If the inlet and outlet temperatures are $T_{i,o}$, respectively, then

$$\eta_I = 1 - \frac{T_E}{T_o - T_i} \ln \frac{T_o}{T_i} , \tag{2.10}$$

where T_E = heat rejection temperature taken in these analyses as 307 K. For systems requiring an intermediate heat exchanger, a 3% penalty (reduction) in η_{TH} is applied to the efficiency which corresponds to about a 30 K temperature drop across the IHX. A 1.5% penalty factor was applied for double-walled steam generators.

The computational algorithm used in the Generomak model, requires as input the plasma beta, the Troyon coefficient, $\beta a B_\phi / I_\phi$, the plasma aspect ratio, $A = 1/\varepsilon = R_T/a$, the plasma elongation, κ, the desired net-electric power, P_e, the maximum toroidal field at the coil, B_m, and the blanket/shield type (i.e., densities, materials, radial standoffs, unit costs, and η_{TH}). From this input a self-consistent set of FPC parameters $(B_\phi, a, I_\phi, q_\psi)$, masses, total recirculating power, BOP size, and costs are computed.

2.2 Departures from Reference Model

The Generomak model contains provision for the alternative fusion-reactor blanket types studied during ESECOM and for alternate current density options. In the instance of the Reverse Field Pinch (V-Li/RFP and RAF-LiPb/RFP), advanced conversion (V-MHD/TOK) and advanced fuel (V-He_3/TOK) variants, some modifications were made to the physics and engineering equations in order to model the devices. The basic physics, BOP technology and costing analyses procedures, however, remain the same between cases.

RFP Variants. Low field resistive-copper coils were assumed for the RFP with the "secondary" PFC taken as a factor of 8 times the TFC mass (vs 0.25 for the reference tokamak). The poloidal beta (β_θ) was nominally fixed at 0.2, with the total beta (β) = $\beta_\theta/2$. An oscillating-field current drive (vs lower-hybrid current drive for tokamaks) was assumed with concomitant reduced unit cost ($0.50/W vs $2.25/W) for this low frequency drive.

The TFC current density for the resistive coils was held constant at 10 MA/m^2 to size the mass, power consumption, and cost, and the plasma current is given by

$$I_\phi = 5\ B_\phi\ (\theta/F)\ , \tag{2.11}$$

where the reversal parameter, $F = B_\phi/\langle B_\phi\rangle$ is -0.12 and the pinch parameter $\theta = B_\theta/\langle B_\theta\rangle$ is 1.6, and $\langle B_\phi\rangle$ is the average toroidal field within the plasma $[\langle B_\phi\rangle \gg |B_\phi|$ for RFPs$]$.

Advanced Conversion and Advanced Fuel Variants.[3] The main improvements in the advanced energy conversion and advanced fuel cases come from direct energy conversion using extracted plasma synchrotron microwave radiation. The synchrotron radiation production requires higher plasma temperatures and higher magnetic fields so extensive modifications to portions of the Generomak model were required.

The ion temperature is 40 keV for the advanced conversion variant and 75 keV for the advanced fuel variant compared to 10–15 keV for the base case. The thermal power is less at these higher temperatures. The thermal power in MW units, for the base case, advanced conversion, and advanced fuel cases are given by,

Base case (10 keV):

$$P_t = 25.6\ (1 + 4\ M_N)\ \langle \beta_i \rangle^2\ B_o^4\ Rab \tag{2.12A}$$

Advanced conversion (40 keV):

$$P_t = 7.2\ (1 + 4\ M_N)\ \langle \beta_i \rangle^2\ B_o^4\ Rab\ . \tag{2.12B}$$

Advanced fuel (75 keV):

$$P_t = 1.35\ (1 + 0.04\ M_N)\ \langle \beta_i \rangle^2\ B_o^4\ Rab\ . \tag{2.12C}$$

The small neutron term (0.04) for the advanced fuel results from the low amount of neutrons (with the advantage of less activation) generated from the D-He_3 fusion reaction.

The fraction of the ion beta to total beta is less at higher ion temperatures because the alpha pressure constitutes a higher fraction of the total beta. The values used were

$$\text{base case:}\quad \beta_i = 0.455\ \beta_t \tag{2.13A}$$

$$\text{MHD case:}\quad \beta_i = 0.41\ \beta_t \tag{2.13B}$$

$$\text{Adv. Fuel Case:}\quad \beta_i = 0.38\ \beta_t \tag{2.13C}$$

The advanced fuel case is based on solid state energy conversion. Only the microwaves (synchrotron radiation) from the plasma are assumed to be converted. The first wall, blanket, and limiter heat is carried out using heat pipes. The gross electric power here is given by

$$P_{ET} = P_u\ \eta_{TH}\ \text{(MWe)} \tag{2.14}$$

where $P_u = 0.491\ P_t$ is the produced microwave power.

The limiters for both advanced variants are assumed to have an area equal to 25% of the first wall

$$A_{tt} = 0.25\ A_w\ (m^2) \tag{2.15}$$

In the advanced conversion case, half of the alpha-particle power is extracted as synchrotron microwave radiation, and, of the remaining half, one-third is radiated to the first wall at the edge. The power to target is, therefore, given by

$$P_{tt} = \frac{0.33\ P_\alpha}{A_{tt}} \tag{2.16}$$

In the advanced fuel case, the power to the target is composed of plasma conduction power, $P_c = 0.138\ P_t$, and bremsstrahlung power, $P_b = 0.333\ P_t$. The heat flux to the target here is

$$P_{tt} = \frac{2/3\ P_c}{A_{tt}} + \frac{P_b}{A_w} \tag{2.17}$$

In the base case the power to the target was taken as a constant (10 MW/m^2) and 80% of the alpha particles were assumed to get to target. The power to the target is used together with the target exposure life to calculate replacement rate.

Coils and Current Density. Three current density options are available in Generomak. These are

$$j_m(MA/m^2) = \frac{96 - 6\ B_m}{1 + (B_m/12)^{1.5}} \qquad \text{Option No. 1} \tag{2.18A}$$

$$j_m(MA/m^2) = \frac{35\ (12/B_m)^{0.8}}{1 + (B_m/12)^{1.5}} \qquad \text{Option No. 2} \tag{2.18B}$$

$$j_m(MA/m^2) = 71\ [1 - (B_m/41.6)^2] \qquad \text{Option No. 3} \tag{2.18C}$$

The standard option for ESECOM analyses was option No. 1, which was the reference option used by Sheffield.[2] Option No. 2 [also used by

Sheffield (Ref. 2, Fig. 4)] gives a somewhat more aggressive current density.

The magnetic fields must be higher in the advanced conversion and advanced fuel case because of the lower power density at higher ion temperature. Current density Option No. 3 was used for these variants, which make use of the latest magnet technology advances. This is discussed in detail in an appendix to the ESECOM report.[3] This approach subdivides the TFC into several conduction circuits and allows each "subcoil" to be tailored according to local magnetic fields. The average current density given by Option No. 3 assumes that the TFC is divided into four subcoils, each operating at ever-increasing critical fields. Higher strength cryogenic steel is assumed and this steel is estimated separately from the winding pack for the coils.

Steel structure not associated with reacting magnet loads was assumed to be 50% of the coil volume in the base case. If Option No. 3 is used (advanced conversion and advanced fuel), then the mass of this structure is estimated as 1/9 of the mass of the rest of the fusion island.

Current Drive Efficiency. The base case assumption is for a constant current-drive efficiency, $I_\phi/P_{CD} = 0.2$ A/W. This represents an aggressive target relative to currently achieved values. An alternative fixed normalized current-drive efficiency,

$$\gamma = (n_e/10^{20})\ I_\phi\ R_T/P_{CD}\ , \tag{2.19}$$

may be specified for tokamak cases. If this option is used, the value of γ and the average plasma temperature, T, may be varied, thereby permitting lower-density, higher-temperature points to be examined. The original Generomak model fixed T at 10 keV and approximates the DT fusion reactivity by,

$$\langle\sigma v\rangle\ (m^3/s) = 1.1 \times 10^{-24}\ T^2\ . \tag{2.20}$$

and the plasma density by,

$$n_e\ (10^{20}/m^3) = \frac{12.4185\beta\ B_o^2}{T} \tag{2.21}$$

A more accurate expression for fusion reactivity was substituted for Eq. (2.20) for use with the γ option,

$$\langle\sigma v\rangle(m^3/s) = \frac{9.46 \times 10^{-18}}{T^{2/3}} (1 - 0.00455\ T^{4/3})\ \exp\ (-20.94/T^{1/3})\ . \tag{2.22}$$

3. ECONOMIC METHODS AND PROCEDURES

This section contains descriptions of the procedures used for the economic characterizations and evaluations. The original Generomak Economics model and calculation procedures[1,2] were used as a starting point, and changes to the original model are discussed below.

The costing methodology and unit costs used in Generomak are generally more severe than used in early fusion reactor designs.[3] Even with this more stringent (realistic) costing model, conditions can be identified where fusion is competitive with alternative energy sources.

3.1 Levelized Cost Procedure

The basic economic methodology and financial parameters used to determine levelized power costs were derived from the Nuclear Energy Cost Data Base (NECDB).[7] The NECDB was developed by Oak Ridge National Laboratory for the Department of Energy, Office of Nuclear Energy and contains a recommended consistent methodology and baseline data and assumptions for performing comparative power generation cost analyses between fission and alternative energy sources. The NECDB is an ongoing program with periodic revisions. The NECDB-3 (1984) version used here, was the most recent published edition at the time the ESECOM analyses began. The provisions of the 1986 Tax Act have not been factored into the analysis but are not expected to have a significant impact on the comparative results.

The methodology uses a year-by-year utility revenue requirements procedure together with levelization techniques to establish a single equivalent cost of electricity (COE) over the economic life of the plant. The procedure is mathematically consistent with basic engineering economic principles and will produce consistent comparisons among alternate energy technologies, including fusion energy.

The NECDB methodology was used to calculate the equivalent fixed charge rate (FCR) on capital. This rate as well as the cost of money, inflation, and tax assumptions are shown in Table 3.1. The FCR is a factor that multiplies the initial capitalized investment to give the

Table 3.1. Reference economic parameters

Plant life, years	30
Plant lead time, years	6
Indirect cost factor	0.375
Contingency factor	0.15
Factor for escalation and interest during construction	1.0856
Nominal capacity factor, %	65
Spare parts multipliers	
• blanket	1.1
• coil	1.2
• limiters	1.2
Effective cost of money	
• nominal dollars	0.09
• constant dollars	0.0283
Inflation rate, %	6
Effective tax rate	0.4816
Tax depreciation life, years	
• overall plant	10
• replaceable blankets, etc.	5
Fixed charge rate	
• nominal dollars	0.165
• constant dollars	0.0844

equivalent annual cost of those charges which are related directly to the initial investment. Both a nominal and constant dollar FCR are given in Table 3.1. The nominal dollar rate produces levelized costs that include inflation. The constant dollar FCR produces levelized costs that are indexed to the buying power in the reference (1986) year. The levelized costs estimated from the analyses are in constant dollars. It should be noted that, even though the constant dollar FCR is used in the calculations, the revenue requirements calculations leading to this rate were done including inflation explicitly and were subsequently adjusted to the constant dollar rate. This procedure is used to avoid tax effects which will distort a comparison if all calculations are made using the constant dollar cost of money.

The FCR used for these analyses differs in two respects from the original Generomak model.[2] First, an 8-year design and construction period was used as the reference value in Ref. 2, compared to the 6-year period used here. The total accumulated interest or Allowance for Funds Used During Construction (AFUDC) as a fraction of total invested capital is a function of lead time. Since the AFUDC rate is an imputed return on capital, AFUDC is not applicable for investment tax credits or tax depreciation. The FCR, therefore is dependent on the amount of AFUDC included in the total invested capital. Secondly the plant is amortized over the full 30 year life, whereas the plant is amortized over the first 20 years of operation in Ref. 1.

The constant dollar (1986) levelized COE is the equivalent annual cost of all cost components divided by the annual electric power production and is expressed as follows:

$$\mathrm{COE\ (mills/kWh)} = \frac{I \times FCR + C_F + C_{OM}}{P_e \times 8760 \times CF} , \qquad (3.1)$$

where

I = initial capitalized investment

C_F = annual fuel cost

C_{OM} = annual O&M cost

P_e = plant net electric rating (MWe)

CF = capacity factor

All costs are expressed in terms of 1986 dollars.

A nominal capacity factor of 65% was used in the analysis. For the advanced-conversion and advanced-fuel cases, however, a 75% capacity factor was the reference. These plants do not have turbines and therefore should show a higher availability.[3] Historic data[8] indicate that turbine generator sets contribute about 10% to plant outages for large-size nuclear and coal-fired plants. In the case of designs with high first-wall loading and concomitant frequent blanket replacement, the capacity factor is adjusted downward to account for the additional time needed for more frequent FPC changeout; the cost of blanket replacement is treated as a fuel change. Based on 90 days/year unscheduled maintenance and 38 days for FPC changeout, the expression for the capacity factor if the changeout rate exceeds 1.54/year is:

$$CF = 0.7534/(1 + 0.1034*R) \quad (3.2)$$

where R is the FPC changeout rate and is equal to the ratio of the neutron wall loading $I_W(MW/m^2)$, to radiation lifetime of the first wall/ blanket system, $I_{WT}(MW{\cdot}year/m^2)$.

3.2 Initial Capitalized Investment

The reference capital investment cost model was taken from the Generomak report.[2] These costs are essentially those used in the Starfire[9] tokamak reactor study updated to January 1983. The costs were further updated to the January 1986 cost basis for the purposes of ESECOM. The complete direct cost model used for the costing basis is given in Table 3.2. The cost model was collapsed to a more manageable size for use in the Generomak code, as shown in Table 3.3. The cost model as shown in Tables 3.2 and 3.3 is for the water-cooled $LiAlO_2$ blanket that was originally used in the starfire-based Generomak model. These costs were adjusted for each of the blankets and environmental and safety innovations considered by ESECOM and are discussed in Sect. 4.

The reference cost model assumes nuclear grade construction with the associated quality assurance required. Cost reductions can be realized if portions of the plant can be built to standards not requiring nuclear grade. This may result from inherent factors, such as the use of $D\text{-}He_3$ fuel or from plant modifications such as the use of low activation materials. Two sets of cost reduction factors were considered by ESECOM as recommended by a study of an inertially confined fusion (ICF) concept[10] and a magnetically confined fusion concept.[11] A tabulation of

Table 3.2. Detailed capital cost model[a]

Account number	Account title	Costs (1986, $M)		
20	Land and Land Rights	5.0		
21	Structures and Improvements	295.0		
21.01	Site Improvement and Facilities			14.8
21.02	Reactor Building			130.1
21.03	Turbine Building			47.8
21.04	Cooling System Structures			10.7
21.05	Electrical Equipment and Power Supply Building			12.2
21.06	Plant Auxiliary Systems Building			4.3
21.07	Hot Cell Building			44.3
21.08	Reactor Service Building			2.5
21.09	Service Water Building			0.9
21.10	Fuel Handling and Storage Building			11.6
21.11	Control Room Building			4.1
21.12	On-Site DC Power — Supply Building			2.7
21.13	Administration Building			1.1
21.14	Site Service Building			1.1
21.15	Cryogenics and Inert Gas Storage Building			1.2
21.16	Security Building			0.5
21.17	Ventilation Stack			2.5
21.18	Spare Parts Allowance			2.6
22	Reactor Plant Equipment	[b]		
22.1	Reactor Equipment		[b]	
22.1.1	Blanket and First Wall			[c]
22.1.2	Shield			[b]
22.1.3	Magnets			[b]
22.1.4	RF Heating and Current Drive			[b,d]
22.1.5	Primary Structure and Support			[b]
22.1.6	Reactor Vacuum			6.2
22.1.7	Power Supply, Switching and Energy Storage			16.5
22.1.8	Impurity Control			3.3
22.1.9	ECRH Plasma Breakdown			3.8

Table 3.2 (continued)

Account number		Account title	Costs (1986, $M)	
22.2		Main Heat Transfer and Transport System	100.3	
	22.2.1	Primary Coolant System		84.0
	22.2.2	Intermediate Coolant System		–
	22.2.3	Limiter Cooling System		8.2
	22.2.4	Residual Heat Removal System		0.8
	22.2.5	Coolant and Gas System		7.3
22.3		Cryogenic Cooling System	21.4	
	22.3.1	Liquid Helium System		17.3
	22.3.2	Liquid Nitrogen System		4.1
22.4		Radioactive Waste Treatment of Disposal	6.3	
	22.4.1	Liquid Waste Processing and Equipment		2.2
	22.4.2	Gaseous Wastes and Off-Gas Processing System		2.4
	22.4.3	Solid Wastes Processing Equipment		1.7
22.5		Fuel Handling and Storage Systems	60.5	
	22.5.1	Fuel Purification Systems		11.7
	22.5.2	Liquefaction		–
	22.5.3	Fuel Preparation Systems		0.5
	22.5.4	Fuel Injection		10.9
	22.5.5	Fuel Storage		2.7
	22.5.6	Tritium Extraction and Recovery		7.1
	22.5.7	Atmospheric Tritium Recovery System		27.6
22.6		Other Reactor Plant Equipment	50.9	
	22.6.1	Maintenance Equipment		50.9
22.7		Instrumentation and Control	31.0	
	22.7.1	Reactor I&C Equipment		10.0
	22.7.2	Monitoring Systems		2.3
	22.7.3	Instrumentation and Transducers		18.7
22.8		Spare Parts Allowance	6.6	

Table 3.2 (continued)

Account number	Account title	Costs (1986, $M)	
23	Turbine Plant Equipment	230.7	
23.1	Turbine-Generators		103.0
23.2	Main Steam System		5.8
23.3	Feed Heating Systems		12.5
23.4	Condensing Systems		25.5
23.5	Other Turbine Plant Equipment		67.7
23.6	Instrumentation and Control (I&C) Equipment		11.6
23.7	Spare Parts Allowance		4.6
24	Electric Plant Equipment	121.2	
24.1	Switchgear		14.7
24.2	Station Service Equipment		20.2
24.3	Switchboards		9.3
24.4	Protective Equipment		2.5
24.5	Electrical Structures and Wiring Containers		20.6
24.6	Power and Control Wiring		42.8
24.7	Electrical Lighting		9.7
24.8	Spare Parts Allowance		1.4
25	Miscellaneous Plant Equipment	47.3	
25.1	Transportation and Lifting Equipment		20.9
25.2	Air and Water Service Systems		16.4
25.3	Communications Equipment		8.3
25.4	Furnishing and Fixtures		1.0
25.5	Spare Parts Allowance		0.7
26	Main Condenser and Heat Reject	59.1	
26.1	Heat Rejection Systems		59.1

[a]Original Generomak water cooled blanket, these costs are adjusted for each case considered.

[b]Variable, depends on blanket.

[c]Treated as a fuel cost.

[d]25% of cost is treated as a fuel cost.

the factors for each of the cost accounts is shown in Table 3.4. Application of either set of cost factors produce approximately the same, ~25%, reduction in bottom-line cost, although large differences exist in individual accounts. These factors, however, are design dependent, may not be fully applicable in all cases, and should be used with care.

Table 3.3. ESECOM reference capital cost model[a, b]

	Account	Direct cost million 1986$	Scale factor[c]	Scale[d]
20.	Land	5.0	0	
21.	Structures & Imp			
	21.1 Reactor bldg & hot cells	174.4	0.67	V_f
	21.2 Other bldg & imp	120.6	0.50	P_t
22.	Reactor plant equipment			
	22.1 Heat trans. & transport	100.3	0.6	P_t
	22.2 Other equipment-1	162.4	0.6	P_t
	22.3 Other equipment-2	44.1	0.67	V_F
23.	Turbine plant equipment	230.7	0.8	P_e
24.	Electric plant equipment	121.2	0.4	P_e
25.	Miscellaneous plant equipment	47.3	0.3	P_e
26.	Main heat rejection system	59.1	0.8	(P_t-P_e)

[a]Direct costs.

[b]Cost model based on the original Generomak water-cooled blanket. These costs are adjusted for each case considered.

[c]Scale factor a in relation

$$C_{NEW} = C_{REF} \left(\frac{X_{NEW}}{X_{REF}}\right)^a$$

$$\begin{aligned} X_{Ref} &= 4085 \text{ for } P_t \text{ (MWt)} \\ &= 2409 \text{ for } V_F \text{ (m)} \\ &= 1200 \text{ for } P_e \text{ [MW(e)]} \\ &= 2885 \text{ for } (P_t-P_e) \text{ (MW)} \end{aligned}$$

[d]Scale with thermal power, P_t, fusion island volume, V_F, electric power P_e, or heat rejected (P_t-P_e).

The Generomak engineering/physics model computes the FPC volumes and reactor thermal power based on the basic plasma parameters, electric power, and other engineering parameters. The estimate of related capital cost is based on a specific FPC volume as well as the thermal and electric power levels. The direct capital costs are scaled to the calculated FPC volume, thermal power, electric power or level of heat

Table 3.4. Safety assurance credit factors[a]

Cost area	Perkins' factor[b]	ICF factor[c]
Blankets	2.0	1.11
Shield	2.0	1.11
Coils	1.44	1.11
Reactor Building and Hot Cells	1.47	4.0
Other Structures and Improvements	1.47	1.15
Heat Transfer and Transport	2.5	1.11
Other Reactor Plant Equipment	1.0	1.11
Turbine Plant Equipment	1.0	1.18
Electrical Plant Equipment	1.75	1.54
Miscellaneous Plant Equipment	1.3	1.67
Heat Reject System	1.25	1.11
Land	1.0	1.18
Indirect Costs	1.25	1.32
O&M Costs	1.0	1.32
All Other Cost Areas	1.0	1.0

[a]Divisor factors applied to cost model accounts.

[b]Source: J. Perkins, Ref. 11.

[c]Source: ICF Study, Ref. 10.

rejected as indicated in Table 3.3. The volume scale factor of 0.67 is that recommended in Ref. 2. The scale factors used for thermal and electric power are those recommended for fission reactor scaling in the NECDB.[7]

The blanket, coil, structure, and shield costs are calculated from the respective volumes together with the average densities and unit costs for the regions. The unit materials costs used in the ESECOM analyses are given in Table 3.5. Both primary TFCs and secondary PFCs are costed with the secondary coil volume expressed as a fraction of the primary coil volume. A 20% coil redundancy is included. The structure volume is assumed to be 50% of the total coil volume for the base

Table 3.5. Unit material costs ($/Kg)

V15Cr5Ti	400
RAF	50
Fe-1422	20
Lithium (Nat)	45
Li_2O (Nat)	45
Thorium	30
Beryllium	500
PCA	50
FLiBe	70
Thorium salt	50
Silicon Carbide	
Blanket	100
Other	30
Carbon	10
BeO	200
PbLi	13
HT-9/Cu	55
Cadmium	1600
Coils	
Super conducting	90
Resistive (RFP)	50
Advanced	130
Advanced coil structure	60
Structure	25
Auxiliary power, $/W	
Current drive (TOK)	2.25
Current drive (RFP)	0.50
Advanced Systems, $M	45
Limiter, $/m^2	60000

case. A 25% contingency is added to the shield cost to account for the shielding of ducts and other apertures in the base shield. The current-drive power is taken as proportional to toroidal plasma current, I_ϕ, in accordance with a fixed efficiency, I_ϕ/P_{CD}. The base case efficiency for tokamaks is 0.2 A/W, although as an alternative a fixed normalized current-drive efficiency, $\gamma = (n_e/10^{20})\, I_\phi R_T/P_{CD}$, may be specified for the tokamak base case.

The current-drive power-supply direct cost uses \$2.25/W for (high frequency) tokamaks and \$0.50/W for (low frequency) RFPs.

The shield, coils, structure, and 75% of the current-drive power supply costs are included in the direct capital investment costs to obtain the total direct costs. The blankets and pumped-limiter impurity control are not permanent and in most cases will need replacement at intervals shorter than the plant life. Similarly, it was assumed that 25% of the current-drive power cost will reoccur on a regular basis. These reoccurring costs are not included in the initial plant investment but instead are treated similar to fission reactor fuel costs, as is discussed below.

The blanket in the V-DHe_3/TOK case is an exception. Here the neutron exposure of the first wall is sufficiently low to assure that the blanket will not have to be replaced during the 30-year plant life. The blanket, therefore, is included in the initial direct capital investment cost for this plant.

An indirect cost factor that includes construction services, engineering and home office services, and field office services is added to the direct costs. These costs in Ref. 2 were assumed to be directly proportional to the design and construction lead time as follows:

$$f_{ind} = (1 + Y/8) \ , \qquad (3.3)$$

where f_{ind} is an indirect cost multiplier and Y is the total lead time in years. Based on this relation, the indirect cost factor is 0.375 for the 6-year lead time used as a reference in ESECOM. For variations around the reference lead time, however, a different relationship was developed. Changes in plant construction/total lead time can affect both direct and indirect costs. Construction labor content tends to grow as construction time is extended; also many of the components of the indirect cost are time dependent. The functional relationship used for the indirect costs for alternate lead times utilizes an analysis performed in connection with an economic study of nuclear fission vs coal-fired plants.[12] The procedures used in that study were adapted to the fusion base case and were normalized to give the base case results for a six year lead time. The resulting relationship factors in both the changes in direct and indirect costs and is given as follows:

$$f_{ind} = 1.12 + 0.0425Y \qquad (3.4)$$

It should be noted that this equation is approximate and detailed engineering/construction analysis is needed to refine the results. Owner's cost, which typically run 5–15% of the direct plus other indirect costs, was not included in the indirect costs.

A 15% contingency factor is added to these total direct plus indirect costs to obtain the total "overnight" costs expressed in 1986 dollars. The total overnight cost is increased by a factor to account for the interest charged during the design and construction period. Assuming an "S" curve construction profile, a simple formula may be derived[2] for the capitalized cost factor in constant dollars. If cost escalation equals the inflation rate, the factor multiplying overnight cost is

$$f_{capo} = \frac{[1.084 + 0.55\ [i - 0.09) + 0.38\ (x - 0.09)]^{Y + 0.61}}{(1 + i)^{Y}} , \qquad (3.5)$$

where f_{capo} is the constant dollar capitalization factor, i is the inflation rate (0.06 for present analysis), x is the effective cost of money (0.09 for present analysis), and Y = design and construction lead time.

Equation 3.5 is used in the Generomak code to calculate the interest during construction. For the reference 6-year lead time, f_{capo} = 1.0856. Other construction cash flow profiles, such as the one in Appendix C of the NECDB,[7] will give somewhat different cost capitalization factors. The overnight cost multiplied by the capitalization factor results in the total capitalized investment cost in constant 1986 dollars. This capitalized cost is converted into a levelized power generation cost using the constant dollar fixed charge rate as shown in Eq. 3.1.

3.3 Operating and Maintenance Costs

Operation and maintenance costs will vary between plant type depending on system complexity, regulatory requirements, security requirements, and maintenance requirements. The operation and maintenance (O&M) costs for the reference case (Li-V/TOK) of 8.9 mills/kWh is based on the same costing procedures used to estimate O&M costs for nuclear fission and coal-fired plants and the manpower requirements estimated in Ref. 2. These procedures are modeled in the OMCOST[13] computer code. A detailed breakdowns of these costs are given in Table 3.6 and the manpower breakdown is given in Table 3.7. The unit O&M costs [mills/kWh(e)] are assumed to scale with electric capacity to the -0.5 power as follows:

$$OM = 8.9 \left(\frac{Pe}{1200}\right)^{-0.5} . \qquad (3.6)$$

3.4 Replacement Costs

The cost of component replacement for fusion plants bears a resemblance to fission reactor fuel costs in that these costs are incurred for components replaced at specific intervals based on their exposure. This fuel-cost category consists of the blanket, limiter, and a portion of the current-drive system (e.g., antennae or window), as well as blanket coolant inventory and makeup, waste disposal, and a charge for fuel and miscellaneous scheduled replacements. A different approach was used to estimate the annual cost of the blankets, limiters and current-drive replacement than was used in Ref. 2 in that the present analysis procedures capitalizes and amortizes these items over their individual periods of service. The present worth of the revenue requirements for

Table 3.6. Nonfuel O&M cost for fusion power plant

Fusion plant O&M costs for ESECOM study		
Net rating of each unit, MWe	1200	
Number of units per plant	1	
Base load capacity factor	0.65	
Thermal input per unit, MWt	2905	
Plant net heat rate, Btu/kWh	8260	
Plant net efficiency, %	41.3	
Annual net generation, million kWh	6837	
Year of Estimate	1986	
Direct costs, $million/year		
Staff onsite (457 persons at $45366)	20.73	
Maintenance material	10.51	
Fixed		8.27
Variable		2.24
Supplies and expenses	7.89	
Fixed		7.18
Variable		0.71
Fees, inspections, reviews	1.04	
Offsite support services	6.44	
Indirect costs, $million/year		
Administrative and general	14.07	
Commercial liability insurance		0.52
Retrospective premium		0.01
Property insurance (primary)		2.60
Property insurance (excess)		1.56
Replacement power insurance		2.39
Other A&G		6.99
Costs, $million/year		
Total fixed directs and indirects		57.7
Total variable directs and indirects		3.0
Total nonfuel O&M		60.7
Unit costs, mills/kWh		
Fixed directs and indirects		8.44
Variable directs and indirects		0.43
Total nonfuel O&M		8.87

Table 3.7. Recommended staffing for an 800 — 1,200 MW(e) reactor

	LWR/LMR	Fusion
Plant Managers Office		
Manager	1	1
Assistant	1	1
Quality assurance	6	8
Environmental control	1	1
Public relations	1	1
Training	12	20
Safety, fire protection	1	1
Administrative services	49	55
Health services	2	2
Security	94	50
Subtotal	168	140
Operations		
Supervision	9	12
Shifts	52	72
Subtotal	61	84
Maintenance		
Supervision	12	16
Crafts	55	73
Peak maintenance annualized	55	73
Subtotal	122	162
Technical and Engineering		
Reactor	5	10
Radiochemical	8	6
Engineering	16	24
Performance, Reports, Technicians	21	30
Subtotal	50	71
Total	401	457

an investment which is depreciated for tax purposes over a period T is as follows:

$$F = \frac{1}{1 - t} \left[1.0 - t \sum_{n=1}^{T} \frac{d_n}{(1 + x)^n} \right], \qquad (3.7)$$

where F is the present worth of a unit investment, t is the effective tax rate (0.4816), d_n is the fraction of cost which is deductible for tax purposes in year n after investment, and x is the nominal dollar cost of money (0.09).

The annual cost of the investment is this present worth of revenue requirements times the capital recovery factor (CRF) calculated using the real cost of money, X_o, and the time the investment is in the fusion plant, L. The CRF is given by,

$$CRF = \frac{X_o (1 + X_o)^L}{(1 + X_o)^L - 1} \qquad (3.8)$$

where $L = I_{WT}/I_W$ is the lifetime of the component.

The 5-year tax depreciation schedule (the same as allowed for fission reactor fuel) is used compared to the 10-year schedule allowed for total plant. A 4-year lead time for blanket, limiter, and current-drive power replacement is assumed, which produces a capitalization factor of 1.0704 from Eq. 3.5. The indirect cost multiplier for these items is taken to be the same as that for other capital investment. Multipliers of 10% and 20% for spare parts are included, respectively, in the blanket and limiter costs.

The out-of-blanket coolant inventory was added to the blanket inventory and no additional indirect or capitalization multipliers were included here. The initial coolant inventory is amortized over the plant life using the plant FCR. In addition, a 2%/year makeup rate is assumed.

The reference waste disposal cost conservatively assumes that the 1 mills/kW(e)h fee now being assessed for fission reactors will also be assessed on fusion reactors. The waste streams from fusion plants, however, are very different than those from a fission plant and it is expected that waste disposal costs for fusion will be less than that for fission. The actual waste cost will vary, depending on the blanket and shield material used.

The reference charge for fuel and scheduled replacement is identical to that in Ref. 2 and is given by,

$$C_f = (0.4 + 24\ FCR_o) \times 10^6\ (\$/year) \qquad (3.9)$$

The use of He_3 for fuel (D-He_3/TOK) involves a greater fuel expense. He_3 is not bred in the blanket as is tritium for the D-T fueled fusion power plants. He_3 is assumed to be obtained from the moon at a cost of \$100/gram leading to a cost of fuel equation given by

$$C_f = [25\ (P_t/5930) + 24\ FCR_o] \times 10^6\ (\$/year) \qquad (3.10)$$

4. COST MODELS AND COSTING ASSUMPTIONS

Unit costs and costing relationships were obtained by updating old cost estimates,[9] through discussions within the ESECOM effort,[3] and, in the case of plant capital investment, through discussions with personnel from an architecture-engineering firm and personnel at the Oak Ridge National Laboratory Fusion Engineering Design Center. Fusion power core physical parameters and average costs are listed in Table 4.1.

In modeling capital-investment costs, the liquid-metal-cooled and FLiBe blanket systems were assumed to need an intermediate heat exchanger. The associated increase in the cost of the reactor building (account 21.1 in Table 3.3) is estimated to be \$19.5 million, and the cost of the heat transfer and transport system (account 22.1) is estimated to increase by \$118.8 million.

For helium-cooled systems, the "other building" cost (account 21.1) was increased by \$1.2 million for additional gas storage. In addition, the heat transfer and transport system costs (account 22.1) were increased by \$82.1 million over the water-cooled base costs.

The fusion breeder (hybrid) concepts are assumed to have dump-tank safety systems as well as on-site fuel reprocessing and refabrication facilities. The cost of these facilities are included as an additional cost account in the capital investment costs. The additional operating costs are included in the operation and maintenance category.

For the RAF-Li/HYB system, \$200 million is added for the dump tanks, fuel transit lines, and beryllium-refabrication direct capital costs. This cost is based on a thermal power of 4085 MWt and scales with thermal power raised to the 0.6. Costs of thorium-metal reprocessing and refabrication are assumed to be similar to those of pyro-reprocessing of liquid-metal reactor fuel.[14] The \$65 million cost for a facility capable of processing 20 tonnes of thorium metal per year includes escalation to 1986 dollars and a 25% contingency. This cost is assumed to scale as the 0.6 power of the throughput. The \$12.5 million per year operating cost scales as the 0.5 power of the throughput.

The cost of the reprocessing plant for the SS-He/HYB fusion breeder is assumed to be \$100 million. The cost of the dump tanks, transit

Table 4.1. Physical parameters and average costs

	V-Li TOK	RAF-He TOK	RAF-LiPb RFP	V-Li RFP	SiC-He TOK	V-FLiBe TOK	V-MHD TOK	V-DHe$_3$ TOK	RAF-Li HYB	SS-He HYB
Blanket:										
Thickness, m	0.71	0.70	0.60	0.315	0.79	1.20	0.17/0.40[a]	0.25/0.50[a]	0.76	0.80
Density, g/cc	2.93	2.0	0.976	0.445	1.50	0.244	0.305	3.0	1.35	1.44
Unit cost, $/kg	118	50	55	400	60	400	400	96	50	67
Gap Thickness, m	0.10	0.10	0.10	0.0	0.40	0.0	0.05/0.10[a]	0.05/0.05[a]	0.10	0.10
Shield:										
Thickness, m	0.83	0.92	0.10	0.45	0.08	0.05	0.74/1.80[a]	0.25/0.50[a]	0.53	0.46
Density, g/cc	7.0	7.0	7.0	6.85	4.80	7.0	5.5	5.5	7.0	7.0
Unit cost, $/kg	20	20	20	81	30	20	20	20	20	20
Coil:										
Density, g/cc	7.9	7.9	7.9	7.9	7.9	7.9	5.4	5.4	7.9	7.9
Unit cost, $/kg	90	90	50	50	90	90	130/60[b]	130/60[b]	90	90
Structure:										
Density, g/cc	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Unit cost, $/kg	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6
Coolant:										
Density, g/cc	0.31	0	6.77	0.608	0	1.92	1.0	0	0.25	0
Unit cost, $/kg	45	0	13	45	0	70	70	0	45	0
Multiplier	3.0	0	3.0	3.0	0	1.0	1.2	0	3.0	0
Additional, m^3	0	0	0	0	0	900	0	0	0	0
Other Materials No. 1										
Density, g/cc	-	-	-	-	-	-	0.216	-	0.99	0.19
Unit cost, $/kg	-	-	-	-	-	-	1600	-	30	50
Multiplier	-	-	-	-	-	-	1.2	-	1.375	1.0
Other Material No. 2:										
Density, g/cc	-	-	-	-	-	-	0.552	-	0.43	0.60
Unit cost, $/kg	-	-	-	-	-	-	500	-	500	500
Multiplier	-	-	-	-	-	-	1.20	-	1.375	1.0
O&M Costs, $M/year	60.6	53.8	60.6	60.6	53.8	60.6	60.6	40.5	62.9	56.1
Other Operating Costs, $M/year	0	0	0	0	0	0	34	0	12.1	7.5

[a]Inner/outer dimensions.

[b]Coils/coil structure unit cost.

lines, and beryllium-fabrication lines and building is \$47 million per gigawatt of fusion power. The estimate for the annual operating cost of the reprocessing facility is 7.5% of the facility capitalized cost.

The advanced systems (V-MHD/TOK and V-DHe$_3$/TOK) contain several costing departures from the base case. For the V-MHD/TOK, the cost of the main heat transport system is included along with the MHD generator as replaceable blanket modules and therefore treated as a fuel cost. For the main heat transport, only miscellaneous small plumbing running external to the magnets is costed.

For the advanced fuel variant, the main heat transport system is synchrotron microwave radiation waveguides costed as

$$30 \text{ M\$ } (P_\mu/2900)^{0.6}$$

where P_μ is the microwave power.

The reference O&M cost for the liquid metal cooled fusion plants was 8.9 mills/kWh (\$60.7 × 10^6 per year at 1200 MWe and 65% capacity factor). This reference cost was reduced by 1 mills/kWh (\$6.8 × 10^6/year) for the helium cooled concepts (RAF-He/TOK, SiC-He/TOK and SS-He/HYB) because of the presumed easier maintenance for these concepts. The O&M cost used for the advanced fuel case (V-DHe3/TOK) was \$40.5 × 10^6 per year because the lower neutron activation rates for this concept would lead to presumed lower maintenance costs. Also the guard force for the hybrid plants was increased by 44 to 94, the level assumed for LWR fission plants. These plants are presumed to have the same security problems as fission plants and will therefore need the same security force.

Fusion island physical parameters and average cost inputs to each of the 10 ESECOM models are given in Table 4.1. The density and unit costs are smeared over the region based on the materials present. Calculations are made on an average region thickness except for the V-MHD/TOK and V-DHe$_3$/TOK cases where inboard and outboard dimensions are specified since they are needed for current density Option No. 3 (Eq. 2.18C). The advanced coils for Option No. 3 are estimated to cost \$130/kg with the cost of the higher strength steel costed at \$60/kg.

The coolant is costed separately from the blanket structure with the volume of coolant inside the blanket increased by a factor to model out-of-blanket inventories. An additional volume may be added to the coolant volume in the model and this was 900 m^3 of FLiBe salt in the V-FLiBe/TOK case. The model can handle other circulating materials in the blankets. The V-MHD/TOK has both cadmium (other material 1) and beryllium (other material 2) in its blanket. The multiplier refers to the ratio of total material to in-blanket inventory. The RAF-Li/HYB has thorium and beryllium for materials 1 and 2 and the SS-He/HYB has thorium molten salt and beryllium in the blanket.

The capital investment cost models for the non-fusion island portion of the ESECOM cases are given in Table 4.2. In addition to the standard accounts, the two hybrid plants also have a fuel recovery plant included.

Table 4.2. Capital investment cost models[a]

(Millions of 1986 dollars)

		V-Li TOK	RAF-He TOK	RAF-LiPb RFP	V-Li RFP	SiC-He TOK	V-FLiBe TOK	V-MHD TOK	V-DHe$_3$ TOK	RAF-Li HYB	SS-He HYB
20.	Land	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
21.	Structures and Improvements										
	21.1 Reactor Bldg. and Hot Cells	193.9	174.4	193.9	193.9	174.4	193.9	193.9	193.9	193.9	193.9
	21.2 Other Bldg. and Imp.	120.6	121.8	120.6	120.6	121.8	120.6	44.0	44.0	120.6	121.8
22.	Reactor Plant Equipment										
	22.1 Heat Transfer and Transport	218.8	182.4	218.8	218.8	182.4	218.8	8.9	30.0[b]	218.8	182.4
	22.2 Other Equipment-1	162.4	162.4	162.4	162.4	162.4	162.4	162.4	80.0	162.4	162.4
	22.3 Other Equipment-2	44.1	44.1	44.1	44.1	44.1	44.1	44.1	44.1	44.1	44.1
23.	Turbine Plant Equipment	230.7	230.7	230.7	230.7	230.7	230.7	0.0	164.5	230.7	230.7
24.	Electric Plant Equipment	121.2	121.2	121.2	121.2	121.2	121.2	121.2	124.9	121.2	121.2
25.	Miscellaneous Plant Equipment	47.3	47.3	47.3	47.3	47.3	47.3	36.8	36.8	47.3	47.3
26.	Main Heat Reject System	59.1	59.1	59.1	59.1	59.1	59.1	20.0[c]	20.0[c]	59.1	59.1
27.	Fuel Recovery Plant										
	27.1 Base Cost	-	-	-	-	-	-	-	-	65.0	100.0
	27.2 Other Costs	-	-	-	-	-	-	-	-	200.0	47.0

[a]Costs scale as indicated in Table 3.3.

[b]Scales as $(0.491\ P_t/2900)^{0.6}$.

[c]Scales as $[(P_t - P_e)/2200]^{0.8}$.

5. GENEROMAK COMPUTER PROGRAM

The original Generomak computer code was developed by Dory and Sheffield for the analyses in Refs. 1 and 2. The basic model was adopted by the ESECOM for the purposes of performing economic trade-offs. In the course of the ESECOM study the original code was extensively modified as discussed in Sects. 2 and 3 of this report. In its final ESECOM form, Generomak is a program written in advanced BASIC (BASICA) for an IBM-PC. It contains in one program access to all 10 fusion plant models studied by ESECOM. This code may be used to estimate the cost of electricity (COE) affect of parameters (such as alternate β scaling or current drive-efficiency) other than those considered by ESECOM.

The list of files contained on the program disk is shown in Table 5.1. The single BASIC program is menu driven and most of the

Table 5.1. Generomak Files

GENERMAK.BAS	GENEROMAK program
ESEFIL.DAT	Data file containing names of available Generomak data models
V-LI-TOK.DAT	Data file for V-Li/TOK ESECOM base or point-of-departure plant
V-LI-RFP.DAT	Data file for ESECOM V-Li/RFP case, the RFP version of V-Li/TOK plant
RAF-HE.DAT	Data file for ESECOM RAF-He/TOK case
PBLI-RFP.DAT	DATA file for ESECOM RAF-LiPb/RFP case
SIC-HE.DAT	Data file for ESECOM SiC-He/TOK case
V-FLIBE.DAT	Data file for ESECOM V-FLIBE/TOK case
ADV-CONV.DAT	Data file for ESECOM advanced conversion, V-MHD/TOK Case
ADV-FUEL.DAT	Data file for ESECOM advanced fuel, V-DHe3/TOK case
LIBE-HYB.DAT	DATA file for ESECOM Lithium cooled, beryllium multiplier, RAF-Li/HYB, Fusion Hybrid Case
MS-HYB.DAT	Datafile for ESECOM molten salt hybrid, SS-He/HYB, case.

entries should be self explanatory. When the program (GENERMAK.BAS) is RUN you are asked first to specify the disk drive on which the data files are located. Enter A, B, C etc. depending on the appropriate drive. The names of the data files available are then shown on the screen. Enter the name of the file desired. (If you want the V-Li/TOK for instance, enter V-LI-TOK.)

The "Main Menu for Plant Specific Data Models" appears next on the screen. The value of any of the model specific data may be changed for a program run. Five sub-menues may be accessed through this main menu. Simply enter the corresponding menu number to access sub-menues. If no change, or no more changes are desired, enter a 0 (zero). An entry of 99 exits the program. Reference physics and engineering parameters for each of the models are presented in Table 5.2.

The five plant-specific data model menues are:

1 = Region Thicknesses

2 = Region Density and Unit Cost

3 = Plasma Physics Parameters

4 = Other Plant Specific Data

5 = Cost Model Data

To change data within these menues, simply enter the corresponding menu number and then enter the revised data. A return, without entering a new data number, will result in a 0 (zero) for the data value (or a blank). The selection of the 0 (zero) menu item will return control to the main plant specific data menu. Reference cost data for each of the models was presented in Tables 4.1 and 4.2.

In the "other plant specific data" sub-menu, item 6 specifies the type of model. The calculation proceeds somewhat differently for different model types as discussed in Sect. 2 and 3 and this option assures that the proper calculations are made. Menu item 7 in this sub-menu specifies the current density option to be used. A 1 specifies the standard option, Eq. 2.18A.; 2 specifies that Eq. 2.18B be used; and Option 3 is used for the advanced concepts (V-MHD/TOK and V-DHe_3/TOK) and is described by Eq. 2.18C and the discussion in Sect. 2.2 and in the ESECOM report.[3]

Table 5.2. Physics and engineering parameters

	V-Li TOK	RAF-He TOK	RAF-LiPb RFP	V-Li RFP	SiC-He TOK	V-FLiBe TOK	V-MHD TOK	V-DHe$_3$ TOK	RAF-Li HYB	SS-He HYB
Plasma Ellipticity, k = b/a	2.5	2.5	1.0	1.0	2.5	2.5	2.5	2.5	2.5	2.5
Aspect Ratio, A = R/a	4.0	4.0	6.0	6.0	4.0	4.0	3.6	3.6	4.0	4.0
Maximum Allowed B ratio	0.7	0.7	1.0	1.0	0.7	0.7	0.7	0.7	0.7	0.7
Total Plasma Beta	0.1	0.1	0.2[a]	0.2[a]	0.1	0.1	0.12	0.12	0.1	0.1
Secondary/Primary Coil Volume, fraction	0.25	0.25	8.0	8.0	0.25	0.25	0.7	0.7	0.25	0.25
Maximum Field in Coils, B_m	10	10	0.69	0.66	10	10	12	16	10	10
Maximum Coil Current Density, 10^6	50	50	10	10	50	50	100	100	50	50
Electrical Conversion Efficiency	0.404	0.40	0.343	0.404	0.383	0.446	0.37	0.768	0.374	0.409
First Wall Fluence Lifetime	20	15	15	20	15	20	20	20	15	7
Fraction of Electric Power Recirculated to BOP	0.06	0.07	0.06	0.06	0.07	0.05	0.05	0.027	0.06	0.08
Blanket Gain	0.272	0.223	0.33	0.272	0.20	0.30	0.30	0.10	1.44	0.80
Capacity Factor	0.65	0.65	0.65	0.65	0.65	0.65	0.75	0.75	0.65	0.65
Current Drive Efficiency, A/W	0.2	0.2	0.4	0.4	0.2	0.2	NA[b]	NA[b]	0.2	0.2

[a]Poloidal Beta

[b]Not applicable, direct cost for auxiliary power of $45 M used.

An additional option; 6 = Delete This Entire Model from Disk, is available on the main menu. This option should be used only if you want to delete permanently the data model you selected (V-LI-TOK, etc.) from the disk. If this option is selected by entering 6, you will be given a second chance. You will be asked:

"If you really want to delete (file name), enter YES (full word)." The file will only be deleted if you enter YES. If you answer YES, the data file will be erased and you will be asked to select a new model. Any other reply will return the main menu.

When the data modifications are finished, an entry of 0 (zero) in the main menu will cause control to move from this menu. If any sub-menu has been accessed you will be asked if you want to save the new data. An answer of N (for no) will cause the program to move to the second main menu. If your answer is Y (for yes) you will be shown the list of names of existing models and asked to enter a model name. If you enter the name of an existing model, it will be replaced. If you enter another model name, not presently on the list, it will be added to the list.

Control now moves to the "Main Menu for Common Variables." Data common to all 10 models are accessible here. There are five sub-menues accessed by this main menu:

1 = Cost/size scaling,

2 = Safety Assurance Cost factors,

3 = Plasma Parameters,

4 = Costing Parameters

5 = Economic Parameters

As with the "Main Plant Specific Data Model Menu," entering the menu item number accesses the sub-menu and a 0 (zero) entry continues the program run. Data is revised by entering the sub-menu item number, and then entering the revised data. This data will be saved from case to case unless control is returned to the first main menu or the program is restarted.

The reference data used in the cost/size scaling menu is that given on Table 3.4. Either the "N" grade (all entries = 1), the Perkins factors, or the ICF safety assurance factor sets (see Table 3.4) may be accessed in the "Safety Assurance Cost Factor" sub-menu.

The values for the items in the "Plasma (and Engineering) Parameters" menu are shown in Table 5.3. Values for items in the "Costing Parameters" sub-menu are shown in Table 5.4 and the reference values of the items in the "Economic Parameters" sub-menu are shown in Table 5.5. In the economic parameter menu, Item 9 specifies the AFUDC multiplier for replacement parts, a zero entry uses the built in relation with a 4 year lead time (see Eq. 3.2). Any other entry will be used directly as a cost multiplier.

A 0 (zero) entry in the "Main Menu for Common Variables" puts the program into the "Run" menu. The program is set up to vary electric

Table 5.3. Plasma and engineering parameters

Wall/plasma radius	1.1
Beta (Ion)/Beta (Electron)	1.0
Beta (Impurity)/Beta (Electron)	0.2
Fraction of alpha power to target	0.8
Fraction of current drive power going to plasma	1.0
Coefficient ("C") in q_ψ equation	1.1
Target fluence lifetime, MW year/m^2	10
Power to target, MW	10
Troyon beta coefficient	0.04
Number of blanket modules per sector	6
Number of coil sectors	20
Normalized current drive efficiency[a,b]	0
Plasma temperature, keV	10

[a]A zero (0) entry specifies use of A/W values for current drive efficiency from Table 5.2. A non-zero entry specifies use of Eqs. 2.19 and 2.22.

[b]Used only for Tokamak reactors.

Table 5.4. Costing parameters

Blanket cost multiplier	1
Coil cost multiplier	1
Current drive cost multiplier	1
Blanket spares multiplier	1.1
Coil redundancy (spares) multiplier	1.2
Limiter spares multiplier	1.2

Table 5.5. Economic parameters

Auxiliary power capacity factor	0.325
Fixed charged rate (constant dollars)	0.0844
Design and construction lead time, years	6
Plant life, years	30
Effective cost of money, nominal dollars	0.09
Inflation/cost escalation rate	0.06
Effective income tax rate	0.4816
AFUDC multiplier[a]	0

[a]Zero specifies the use of Eq. 3.5 with 4 year lead time.

power (P_e) and/or B_m (BMAX) automatically. One need only specify the minimum values for P_e or B_m, the number of step or calculations involving each variable and the increment between steps. For instance, if the calculation is to be made for B_m = 8, 10, and 12; then the minimum value specified for BMAX (menu item 4) is 8; the number of steps (item 5) is 3 and the delta between steps (menu item 6) is 2.

An entry of 70 keeps the entire model as changed and goes to the "Main Menu for Common Variables". An entry of 80, keeps the reactor type model (i.e., V-LI-TOK), returns the common variables to their original value and goes to the "Main Plant Specific Data Model Menu". An entry of 90 returns to the start of program, thus removing any changes that were not saved on disk. An entry of 99 exits the program.

If the data are correct, input a 0 (zero). You will be asked to input a title for the job; this title will appear on each sheet of output.

A sample output for the V-Li/TOK base case is shown in Fig. 5.1. Two pages of output are produced for each case. The first page shows

ORNL–DWG 88–4370 ETD (PART A)

```
V-Li/TOK BASECASE
        02-25-1988

V-LI-TOK  V-LI-TOK  V-LI-TOK  V-LI-TOK  V-LI-TOK

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)                       0.100
ASPECT RATIO OF TORUS(R/a)(ASPECT)            4.0
PLASMA ELLIPTICITY(ELLIP)                     2.500
MAXIMUM FIELD IN COIL(BMAX)                  10.000
MAXIMUM ALLOWED BETA RATIO(BRMAX)             0.70
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)        0.71      0.71
GAP THICKNESS 1 AND 2(DELG1,DELG2)            0.10      0.10
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)         0.83      0.83
AVERAGE CURRENT DENSITY IN COIL(DJBAR)       20.446
NUMBER OF ITERATIONS(NIT)                    21
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP      0.838     0.018     0.323
B4RAB(T^4*M^3) AND DENSITY(1/E+20)       10820          2.2900
PLASMA RADIUS(AP)                             1.472
MAJOR RADIUS(RO)                              5.887
TOROIDAL FIELD IN PLASMA(BO)                  4.294
BETA RATIO(BRATIO)                            0.429
MEAN PLASMA RADIUS(ABAR)                      2.327
NEUTRON WALL LOADING(PWN)                     3.195
PLANT AVAILABILITY(FAV)                       0.650
CURRENT DRIVE(CURRD)                         15.801
FIRST WALL AREA,M^2(AWALL)                  716.5
ALPHA POWER,MWT(PALPHA)                     572.3
NEUTRON POWER,MWT(PNEUT)                   2289.3
FUSION POWER,MWT(PFUS)                     2861.6
NUCLEAR POWER,MWT(PNUC)                    3484.3
AUXILLIARY POWER,MWe(PAUX)                   79.0
TOTAL THERMAL POWER,MWT(PTH)               3563.3
AVAILABLE THERMAL POWER,MWT(PTAV)          3367.9
ELECTRIC POWER(PEL)                        1200.0
RECIRC. POWER FRACTION                        0.12
SAFETY FACTOR                                 2.268
```

Fig. 5.1. Output for V-Li/TOK base case.

ORNL–DWG 88–4370 ETD (PART B)

V-Li/TOK BASECASE

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	526.2	978.6	214.8	53.7	134.2	2669
WEIGHT	1704.7	6850.5	1696.8	424.2	805.4	11482
COST	207.4	137.0	152.7	38.2	20.6	

NEUTRON WALL LOADING(PWN) 3.195
MASS POWER DENSITY,MPD(KWe/TONNE) 104.51

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	320.3	
REACTOR BLDG. AND HOT CELLS		207.6
OTHER STRUCTURES AND IMPROV.		112.6
REACTOR PLANT EQUIPMENT	880.3	
SHIELD		137.0
COILS		190.9
STRUCTURE		20.6
AUX. HEATER		133.3

TOTAL NUCLEAR ISLAND		481.8
HEAT TRANSFER AND TRANSPORT		201.6
OTHER REACT PLANT EQUIP		196.8
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	45.4	
MAIN COND. HEAT REJECTION	50.4	

TOTAL DIRECT COST	1653.2	
INDIRECT COSTS	619.9	

TOTAL DIRECT+INDIRECT	2273.1	
CONTINGENCY	341.0	

TOTAL OVERNIGHT COST	2614.1	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		239.52		35.05
OPER AND MAINT		60.61		8.87
FUEL CHARGE BREAKDOWN				
BLANKETS	44.47		6.51	
LIMITERS	3.90		0.57	
AUXILIARY HEAT	5.30		0.78	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		62.93		9.21
		-------		-------
TOTAL COST		363.06		53.13

Fig. 5.1 (continued)

some of the input parameters and the output of the physics calculations. The second page shows the volume, weight and costs calculated for the FPC; the neutron wall loading and mass power density; a breakdown of the components of the capital investment cost; and a breakdown by cost component of the Power Generation Cost (cost of electricity, COE). The output for the 10 ESECOM cases, for nuclear grade ("N" stamp) construction, is given in Appendix B of this report. Costs for full safety assurance are about 25% less (in COE).

The average running time for each case is about 20 seconds with further delay for printout.

Appendix A

ACRONYMS, NOMENCLATURE, AND DEFINITION OF TERMS

Acronyms and Nomenclature

AFUDC	allowance for funds used during construction
COE	cost of electricity
ESECOM	Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy
FCR	fixed charge rate
FPC	fusion power core
ICF	inertially confined fusion
IHX	intermediate heat exchanger
NECDB	Nuclear Energy Cost Data Base
O&M	operation and maintenance
PFC	poloidal field coil
TFC	toroidal field coil
D-T	deuterium tritium fuel
D-He3	deuterium helium 3 fuel

Definition of Terms

A	aspect ration (R_T/a)
A_{tt}	area of target (m^2)
a	plasma minor radius, small dimension (m)
a_w	first wall minor radius, small dimension (m)
b	plasma minor radius, large dimension (m)
B_ϕ	magnetic field in plasma (T)
B_m	maximum field on primary coil (T)
B_θ	circularized plasma poloidal field (T)
CF	capacity factor
C_F	annual cost of fuel-like items (M$/year)
C_f	annual cost of miscellaneous fuel (M$/year)
C_{OM}	annual cost of operation and maintenance tax deductible depreciation

d_n	tax deductible depreciation fraction in year (M$/year)
F	RFP reversal parameter, or present worth of revenue requirements factor
FCR_o	constant dollar fixed charge rate (fraction/year)
f_{AUX}	fraction of electric power recirculated to power plant (excludes current drive power)
f_{capo}	capitalization factor in constant dollars
f_{CD}	fraction of current drive power delivered to plasma
f_{ind}	cost multiplier for indirect costs
g	blanket energy multiplication gain
i	inflation rate
I_o	plasma current (MA)
I_w	neutron wall loading (MW/m^2)
$I_{w\tau}$	first wall radiation lifetime (MW years/m^2)
j_m	coil average current density (kA/cm^2)
L	blanket life in fusion plant (years)
M_N	Neutron energy multiplier in blanket
P_b	bremsstrahlung power to target (MW)
P_c	plasma conduction power to target (MW)
P_{CD}	current drive power (MW)
P_e	electric power to grid (MW)
P_{ET}	total electric power (MW)
P_f	fusion power (MW)
P_N	neutron power (MW)
P_t	total thermal power (MW)
P_{TH}	available thermal power (MW)
P_{tt}	power to target (MW)
P_u	produced microwave power (MW)
P_α	alpha particle power (MW)
q_a	edge plasma safety factor
q_ψ	flux defined safety factor
R	replacement rate for blanket modules ($year^{-1}$)
R_T	major radius of plasma (m)
T	plasma temperature (KeV), or tax depreciation period (years)
T_E	heat rejection temperature (°K)

T_i	primary loop inlet temperature (°K)
T_o	primary loop outlet temperature (°K)
t	combined federal and state income tax rate (0.4816)
X	nominal dollar effective cost of money (0.09)
X_o	constant dollar effective cost of money (0.0283)
Y	power plant design and construction lead time (years)

Greek

β	total plasma beta
β_e	electron beta
β_i	ion beta
β_Z	impurity ion beta
β_θ	poloidal beta
Δb	radial thickness of blanket (m)
Δd	radial thickness of coil dewar (m)
Δg	radial thickness of maintenance/service gap (m)
ΔS	radial thickness of shield (m)
ϵ	inverse aspect ratio (1/A)
θ	RFP pinch parameter
κ	plasma elongation (b/a)
η_e	plasma density ($10^{20}/m^3$)
η_{TH}	thermal to electric conversion efficiency
η_I	ideal thermal efficiency
$\langle\sigma v\rangle$	fusion reactivity (m^3/s)

Appendix B

OUTPUT FROM ESECOM CASES

There were ten fusion reactors considered in the ESECOM analyses. The computer output for each of these ten cases based on full nuclear grade costing are shown in Figs. B.1—B.10.

ORNL–DWG 88–4371 ETD (PART A)

ESECOM BASE CASE - Li COOLED FIRST WALL TOKAMAK
02-25-1988

V-LI-TOK V-LI-TOK V-LI-TOK V-LI-TOK V-LI-TOK

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.100		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	4.0		
PLASMA ELLIPTICITY(ELLIP)	2.500		
MAXIMUM FIELD IN COIL(BMAX)	10.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.71	0.71	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.10	0.10	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.83	0.83	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	20.446		
NUMBER OF ITERATIONS(NIT)	21		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.838	0.018	0.323
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	10820	2.2900	
PLASMA RADIUS(AP)	1.472		
MAJOR RADIUS(RO)	5.887		
TOROIDAL FIELD IN PLASMA(BO)	4.294		
BETA RATIO(BRATIO)	0.429		
MEAN PLASMA RADIUS(ABAR)	2.327		
NEUTRON WALL LOADING(PWN)	3.195		
PLANT AVAILABILITY(FAV)	0.650		
CURRENT DRIVE(CURRD)	15.801		
FIRST WALL AREA,M^2(AWALL)	716.5		
ALPHA POWER,MWT(PALPHA)	572.3		
NEUTRON POWER,MWT(PNEUT)	2289.3		
FUSION POWER,MWT(PFUS)	2861.6		
NUCLEAR POWER,MWT(PNUC)	3484.3		
AUXILLIARY POWER,MWe(PAUX)	79.0		
TOTAL THERMAL POWER,MWT(PTH)	3563.3		
AVAILABLE THERMAL POWER,MWT(PTAV)	3367.9		
ELECTRIC POWER(PEL)	1200.0		
RECIRC. POWER FRACTION	0.12		
SAFETY FACTOR	2.268		

Fig. B.1. Output for ESECOM basecase, V–Li/TOK.

ORNL–DWG 88–4371 ETD (PART B)

ESECOM BASE CASE - Li COOLED FIRST WALL TOKAMAK

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	526.2	978.6	214.8	53.7	134.2	2669
WEIGHT	1704.7	6850.5	1696.8	424.2	805.4	11482
COST	207.4	137.0	152.7	38.2	20.6	

NEUTRON WALL LOADING(PWN)	3.195
MASS POWER DENSITY,MPD(KWe/TONNE)	104.51

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	320.3	
REACTOR BLDG. AND HOT CELLS		207.6
OTHER STRUCTURES AND IMPROV.		112.6
REACTOR PLANT EQUIPMENT	880.3	
SHIELD		137.0
COILS		190.9
STRUCTURE		20.6
AUX. HEATER		133.3

TOTAL NUCLEAR ISLAND		481.8
HEAT TRANSFER AND TRANSPORT		201.6
OTHER REACT PLANT EQUIP		196.8
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	45.4	
MAIN COND. HEAT REJECTION	50.4	

TOTAL DIRECT COST	1653.2	
INDIRECT COSTS	619.9	

TOTAL DIRECT+INDIRECT	2273.1	
CONTINGENCY	341.0	

TOTAL OVERNIGHT COST	2614.1	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		239.52		35.05
OPER AND MAINT		60.61		8.87
FUEL CHARGE BREAKDOWN				
BLANKETS	44.47		6.51	
LIMITERS	3.90		0.57	
AUXILIARY HEAT	5.30		0.78	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		62.93		9.21
		-------		-------
TOTAL COST		363.06		53.13

Fig. B.1 (continued)

ORNL--DWG 88-4372 ETD (PART A)

He COOLED RAF FIRST WALL TOKAMAK
02-25-1988

RAF-HE RAF-HE RAF-HE RAF-HE RAF-HE

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.100		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	4.0		
PLASMA ELLIPTICITY(ELLIP)	2.500		
MAXIMUM FIELD IN COIL(BMAX)	10.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.70	0.70	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.10	0.10	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.92	0.92	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	20.446		
NUMBER OF ITERATIONS(NIT)	22		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.876	0.018	0.331
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	11449	2.2470	
PLASMA RADIUS(AP)	1.519		
MAJOR RADIUS(RO)	6.075		
TOROIDAL FIELD IN PLASMA(BO)	4.254		
BETA RATIO(BRATIO)	0.425		
MEAN PLASMA RADIUS(ABAR)	2.401		
NEUTRON WALL LOADING(PWN)	3.176		
PLANT AVAILABILITY(FAV)	0.650		
CURRENT DRIVE(CURRD)	16.150		
FIRST WALL AREA,M^2(AWALL)	762.8		
ALPHA POWER,MWT(PALPHA)	605.6		
NEUTRON POWER,MWT(PNEUT)	2422.3		
FUSION POWER,MWT(PFUS)	3027.8		
NUCLEAR POWER,MWT(PNUC)	3568.0		
AUXILLIARY POWER,MWe(PAUX)	80.7		
TOTAL THERMAL POWER,MWT(PTH)	3648.8		
AVAILABLE THERMAL POWER,MWT(PTAV)	3442.9		
ELECTRIC POWER(PEL)	1200.0		
RECIRC. POWER FRACTION	0.13		
SAFETY FACTOR	2.268		

Fig. B.2. Output for RAF-He/TOK.

ORNL–DWG 88–4372 ETD (PART B)

He COOLED RAF FIRST WALL TOKAMAK

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	549.5	1153.8	227.2	56.8	142.0	2966
WEIGHT	1099.1	8076.4	1795.1	448.8	852.1	12271
COST	60.4	161.5	161.6	40.4	21.8	

NEUTRON WALL LOADING(PWN) 3.176
MASS POWER DENSITY,MPD(KWe/TONNE) 97.79

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	315.5	
REACTOR BLDG. AND HOT CELLS		200.4
OTHER STRUCTURES AND IMPROV.		115.1
REACTOR PLANT EQUIPMENT	894.4	
SHIELD		161.5
COILS		201.9
STRUCTURE		21.8
AUX. HEATER		136.3

TOTAL NUCLEAR ISLAND		521.6
HEAT TRANSFER AND TRANSPORT		170.4
OTHER REACT PLANT EQUIP		202.4
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	45.7	
MAIN COND. HEAT REJECTION	51.8	

TOTAL DIRECT COST	1664.3	
INDIRECT COSTS	624.1	

TOTAL DIRECT+INDIRECT	2288.5	
CONTINGENCY	343.3	

TOTAL OVERNIGHT COST	2631.8	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		241.14		35.29
OPER AND MAINT		53.80		7.87
FUEL CHARGE BREAKDOWN				
BLANKETS	16.35		2.39	
LIMITERS	4.12		0.60	
AUXILIARY HEAT	6.76		0.99	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		36.49		5.34
		-------		-------
TOTAL COST		331.43		48.51

Fig. B.2 (continued)

ORNL-DWG 88-4373 ETD (PART A)

RAF STRUCTURE LiPb BREEDER RFP
02-25-1988

PBLI-RFP PBLI-RFP PBLI-RFP PBLI-RFP PBLI-RFP
******NC/RFP*******

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.200	
ASPECT RATIO OF TORUS(R/a)(ASPECT)	6.0	
PLASMA ELLIPTICITY(ELLIP)	1.000	
MAXIMUM FIELD IN COIL(BMAX)	0.690	
MAXIMUM ALLOWED BETA RATIO(BRMAX)	1.00	
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.60	0.60
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.10	0.10
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.10	0.10
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	10.000	
NUMBER OF ITERATIONS(NIT)	10	
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.338	0.167
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	3111	8.2003
PLASMA RADIUS(AP)	0.781	
MAJOR RADIUS(RO)	4.686	
TOROIDAL FIELD IN PLASMA(BO)	0.431	
BETA RATIO(BRATIO)	0.625	
MEAN PLASMA RADIUS(ABAR)	0.781	
NEUTRON WALL LOADING(PWN)	16.567	
PLANT AVAILABILITY(FAV)	0.650	
CURRENT DRIVE(CURRD)	22.438	
FIRST WALL AREA,M^2(AWALL)	158.9	
ALPHA POWER,MWT(PALPHA)	658.3	
NEUTRON POWER,MWT(PNEUT)	2633.1	
FUSION POWER,MWT(PFUS)	3291.3	
NUCLEAR POWER,MWT(PNUC)	4160.2	
AUXILLIARY POWER,MWe(PAUX)	56.1	
TOTAL THERMAL POWER,MWT(PTH)	4216.3	
AVAILABLE THERMAL POWER,MWT(PTAV)	3990.8	
ELECTRIC POWER(PEL)	1199.9	
RECIRC. POWER FRACTION	0.12	
SAFETY FACTOR	0.194	
REVERSAL PARAMETER	0.12	
PINCH PARAMETER	1.60	

Fig. B.3. Output for RAF-LiPb/RFP.

ORNL–DWG 88–4373 ETD (PART B)

RAF STRUCTURE LiPb BREEDER RFP

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	128.7	37.2	14.3	114.6	64.5	428
WEIGHT	996.6	260.5	113.2	905.6	386.9	2663
COST	18.9	5.2	5.7	45.3	9.9	

NEUTRON WALL LOADING(PWN) %16.567
MASS POWER DENSITY,MPD(KWe/TONNE) 450.63

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	183.7	
REACTOR BLDG. AND HOT CELLS		61.2
OTHER STRUCTURES AND IMPROV.		122.5
REACTOR PLANT EQUIPMENT	489.5	
SHIELD		5.2
COILS		50.9
STRUCTURE		9.9
AUX. HEATER		21.0

TOTAL NUCLEAR ISLAND		87.1
HEAT TRANSFER AND TRANSPORT		223.0
OTHER REACT PLANT EQUIP		179.4
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	47.8	
MAIN COND. HEAT REJECTION	61.2	

TOTAL DIRECT COST	1139.1	
INDIRECT COSTS	427.2	

TOTAL DIRECT+INDIRECT	1566.3	
CONTINGENCY	234.9	

TOTAL OVERNIGHT COST	1801.2	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		165.04		24.16
OPER AND MAINT		60.61		8.87
FUEL CHARGE BREAKDOWN				
BLANKETS	13.44		1.97	
LIMITERS	4.48		0.66	
AUXILIARY HEAT	4.65		0.68	
OTHER FUEL	2.43		0.36	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		31.83		4.66
		-------		-------
TOTAL COST		257.48		37.69

Fig. B.3 (continued)

ORNL–DWG 88–4374 ETD (PART A)

Li COOLED V FIRST WALL RFP
02-25-1988

V-LI-RFP V-LI-RFP V-LI-RFP V-LI-RFP V-LI-RFP
******NC/RFP*******

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.200	
ASPECT RATIO OF TORUS(R/a)(ASPECT)	6.0	
PLASMA ELLIPTICITY(ELLIP)	1.000	
MAXIMUM FIELD IN COIL(BMAX)	0.660	
MAXIMUM ALLOWED BETA RATIO(BRMAX)	1.00	
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.32	0.32
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.00	0.00
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.45	0.45
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	10.000	
NUMBER OF ITERATIONS(NIT)	9	
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.317	0.173
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	2738	7.6861
PLASMA RADIUS(AP)	0.782	
MAJOR RADIUS(RO)	4.689	
TOROIDAL FIELD IN PLASMA(BO)	0.417	
BETA RATIO(BRATIO)	0.632	
MEAN PLASMA RADIUS(ABAR)	0.782	
NEUTRON WALL LOADING(PWN)	%14.558	
PLANT AVAILABILITY(FAV)	0.650	
CURRENT DRIVE(CURRD)	21.738	
FIRST WALL AREA,M^2(AWALL)	159.2	
ALPHA POWER,MWT(PALPHA)	579.2	
NEUTRON POWER,MWT(PNEUT)	2316.9	
FUSION POWER,MWT(PFUS)	2896.2	
NUCLEAR POWER,MWT(PNUC)	3526.4	
AUXILLIARY POWER,MWe(PAUX)	54.3	
TOTAL THERMAL POWER,MWT(PTH)	3580.7	
AVAILABLE THERMAL POWER,MWT(PTAV)	3379.8	
ELECTRIC POWER(PEL)	1200.0	
RECIRC. POWER FRACTION	0.12	
SAFETY FACTOR	0.194	
REVERSAL PARAMETER	0.12	
PINCH PARAMETER	1.60	

Fig. B.4. Output for V-Li/RFP.

ORNL–DWG 88–4374 ETD (PART B)

Li COOLED V FIRST WALL RFP

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	59.3	145.8	13.6	108.9	61.3	457
WEIGHT	62.5	998.4	107.6	860.4	367.6	2396
COST	13.2	80.9	5.4	43.0	9.4	

NEUTRON WALL LOADING(PWN)	%14.558
MASS POWER DENSITY,MPD(KWe/TONNE)	500.74

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	176.9	
REACTOR BLDG. AND HOT CELLS		64.0
OTHER STRUCTURES AND IMPROV.		112.9
REACTOR PLANT EQUIPMENT	525.8	
SHIELD		80.9
COILS		48.4
STRUCTURE		9.4
AUX. HEATER		20.4

TOTAL NUCLEAR ISLAND		159.1
HEAT TRANSFER AND TRANSPORT		202.2
OTHER REACT PLANT EQUIP		164.6
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	45.5	
MAIN COND. HEAT REJECTION	50.7	

TOTAL DIRECT COST	1155.8	
INDIRECT COSTS	433.4	

TOTAL DIRECT+INDIRECT	1589.2	
CONTINGENCY	238.4	

TOTAL OVERNIGHT COST	1827.6	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		167.46		24.51
OPER AND MAINT		60.61		8.87
FUEL CHARGE BREAKDOWN				
BLANKETS	10.58		1.55	
LIMITERS	3.94		0.58	
AUXILIARY HEAT	3.03		0.44	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		26.81		3.92
		-------		-------
TOTAL COST		254.88		37.30

Fig. B.4 (continued)

ORNL–DWG 88–4375 ETD (PART A)

```
He COOLED SiC STRUCTURE TOKAMAK
        02-25-1988

SIC-HE  SIC-HE  SIC-HE  SIC-HE  SIC-HE

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)                          0.100
ASPECT RATIO OF TORUS(R/a)(ASPECT)               4.0
PLASMA ELLIPTICITY(ELLIP)                        2.500
MAXIMUM FIELD IN COIL(BMAX)                     10.000
MAXIMUM ALLOWED BETA RATIO(BRMAX)                0.70
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)           0.79      0.79
GAP THICKNESS 1 AND 2(DELG1,DELG2)               0.40      0.40
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)            1.08      1.08
AVERAGE CURRENT DENSITY IN COIL(DJBAR)          20.446
NUMBER OF ITERATIONS(NIT)                       25
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP         0.972     0.019     0.394
B4RAB(T^4*M^3) AND DENSITY(1/E+20)           12197         1.8653
PLASMA RADIUS(AP)                                1.756
MAJOR RADIUS(RO)                                 7.024
TOROIDAL FIELD IN PLASMA(BO)                     3.876
BETA RATIO(BRATIO)                               0.388
MEAN PLASMA RADIUS(ABAR)                         2.777
NEUTRON WALL LOADING(PWN)                        2.530
PLANT AVAILABILITY(FAV)                          0.650
CURRENT DRIVE(CURRD)                            17.015
FIRST WALL AREA,M^2(AWALL)                    1019.9
ALPHA POWER,MWT(PALPHA)                        645.1
NEUTRON POWER,MWT(PNEUT)                      2580.6
FUSION POWER,MWT(PFUS)                        3225.7
NUCLEAR POWER,MWT(PNUC)                       3741.8
AUXILLIARY POWER,MWe(PAUX)                      85.1
TOTAL THERMAL POWER,MWT(PTH)                  3826.9
AVAILABLE THERMAL POWER,MWT(PTAV)             3607.8
ELECTRIC POWER(PEL)                           1200.0
RECIRC. POWER FRACTION                           0.13
SAFETY FACTOR                                    2.268
```

Fig. B.5. Output for SiC-He/TOK.

ORNL-DWG 88-4375 ETD (PART B)

He COOLED SiC STRUCTURE TOKAMAK

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	827.1	1913.1	288.1	72.0	180.1	4574
WEIGHT	1240.6	9183.0	2276.2	569.1	1080.5	14349
COST	81.9	275.5	204.9	51.2	27.7	

NEUTRON WALL LOADING(PWN) 2.530
MASS POWER DENSITY,MPD(KWe/TONNE) 83.63

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	385.4	
REACTOR BLDG. AND HOT CELLS		267.5
OTHER STRUCTURES AND IMPROV.		117.9
REACTOR PLANT EQUIPMENT	1102.0	
SHIELD		275.5
COILS		256.1
STRUCTURE		27.7
AUX. HEATER		143.6

TOTAL NUCLEAR ISLAND		702.8
HEAT TRANSFER AND TRANSPORT		175.4
OTHER REACT PLANT EQUIP		223.8
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	46.4	
MAIN COND. HEAT REJECTION	54.8	

TOTAL DIRECT COST	1945.4	
INDIRECT COSTS	729.5	

TOTAL DIRECT+INDIRECT	2675.0	
CONTINGENCY	401.2	

TOTAL OVERNIGHT COST	3076.2	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		281.86		41.25
OPER AND MAINT		53.80		7.87
FUEL CHARGE BREAKDOWN				
BLANKETS	18.10		2.65	
LIMITERS	4.39		0.64	
AUXILIARY HEAT	5.95		0.87	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		37.70		5.52
		-------		-------
TOTAL COST		373.36		54.64

Fig. B.5 (continued)

ORNL-DWG 88-4376 ETD (PART A)

FLiBe COOLANT/BREEDER V FIRST WALL TOKAMAK
02-25-1988

V-FLIBE V-FLIBE V-FLIBE V-FLIBE V-FLIBE

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.100		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	4.0		
PLASMA ELLIPTICITY(ELLIP)	2.500		
MAXIMUM FIELD IN COIL(BMAX)	10.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	1.20	1.20	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.00	0.00	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.05	0.05	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	20.446		
NUMBER OF ITERATIONS(NIT)	19		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.731	0.018	0.279
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	9468	2.6418	
PLASMA RADIUS(AP)	1.280		
MAJOR RADIUS(R0)	5.119		
TOROIDAL FIELD IN PLASMA(B0)	4.612		
BETA RATIO(BRATIO)	0.461		
MEAN PLASMA RADIUS(ABAR)	2.023		
NEUTRON WALL LOADING(PWN)	3.699		
PLANT AVAILABILITY(FAV)	0.650		
CURRENT DRIVE(CURRD)	14.755		
FIRST WALL AREA,M^2(AWALL)	541.6		
ALPHA POWER,MWT(PALPHA)	500.8		
NEUTRON POWER,MWT(PNEUT)	2003.2		
FUSION POWER,MWT(PFUS)	2503.9		
NUCLEAR POWER,MWT(PNUC)	3104.9		
AUXILLIARY POWER,MWe(PAUX)	73.8		
TOTAL THERMAL POWER,MWT(PTH)	3178.7		
AVAILABLE THERMAL POWER,MWT(PTAV)	3006.3		
ELECTRIC POWER(PEL)	1200.0		
RECIRC. POWER FRACTION	0.11		
SAFETY FACTOR	2.268		

Fig. B.6. Output for V-FLiBe/TOK.

ORNL--DWG 88--4376 ETD (PART B)

FLiBe COOLANT/BREEDER V FIRST WALL TOKAMAK

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	742.8	46.6	169.2	42.3	105.7	2507
WEIGHT	1607.5	326.1	1336.6	334.1	634.5	4239
COST	179.6	6.5	120.3	30.1	16.2	

NEUTRON WALL LOADING(PWN) 3.699
MASS POWER DENSITY,MPD(KWe/TONNE) 283.10

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	305.5	
REACTOR BLDG. AND HOT CELLS		199.1
OTHER STRUCTURES AND IMPROV.		106.4
REACTOR PLANT EQUIPMENT	670.8	
SHIELD		6.5
COILS		150.4
STRUCTURE		16.2
AUX. HEATER		124.5

TOTAL NUCLEAR ISLAND		297.6
HEAT TRANSFER AND TRANSPORT		188.2
OTHER REACT PLANT EQUIP		185.0
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	43.9	
MAIN COND. HEAT REJECTION	43.7	

TOTAL DIRECT COST	1420.8	
INDIRECT COSTS	532.8	

TOTAL DIRECT+INDIRECT	1953.7	
CONTINGENCY	293.0	

TOTAL OVERNIGHT COST	2246.7	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		205.86		30.13
OPER AND MAINT		60.61		8.87
FUEL CHARGE BREAKDOWN				
BLANKETS	42.69		6.25	
LIMITERS	3.41		0.50	
AUXILIARY HEAT	5.54		0.81	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		60.91		8.91
		-------		-------
TOTAL COST		327.37		47.91

Fig. B.6 (continued)

ORNL-DWG 88-4377 ETD (PART A)

V FIRST WALL WITH MHD CONVERSION TOKAMAK
02-25-1988

ADV-CONV ADV-CONV ADV-CONV ADV-CONV ADV-CONV

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.120		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	3.6		
PLASMA ELLIPTICITY(ELLIP)	2.500		
MAXIMUM FIELD IN COIL(BMAX)	12.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.17	0.40	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.05	0.10	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.74	1.80	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	65.083		
NUMBER OF ITERATIONS(NIT)	15		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.405	0.040	0.439
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	31594	1.3315	
PLASMA RADIUS(AP)	1.401		
MAJOR RADIUS(RO)	5.045		
TOROIDAL FIELD IN PLASMA(BO)	5.978		
BETA RATIO(BRATIO)	0.498		
MEAN PLASMA RADIUS(ABAR)	2.216		
NEUTRON WALL LOADING(PWN)	3.742		
PLANT AVAILABILITY(FAV)	0.750		
CURRENT DRIVE(CURRD)	25.135		
FIRST WALL AREA,M^2(AWALL)	584.6		
ALPHA POWER,MWT(PALPHA)	550.6		
NEUTRON POWER,MWT(PNEUT)	2202.5		
FUSION POWER,MWT(PFUS)	2753.2		
NUCLEAR POWER,MWT(PNUC)	3413.9		
AUXILLIARY POWER,MWe(PAUX)	0.0		
TOTAL THERMAL POWER,MWT(PTH)	3413.9		
AVAILABLE THERMAL POWER,MWT(PTAV)	3413.9		
ELECTRIC POWER(PEL)	1200.0		
RECIRC. POWER FRACTION	0.05		
SAFETY FACTOR	2.168		

Fig. B.7. Output for V-MHD/TOK.

ORNL--DWG 88-4377 ETD (PART B)

V FIRST WALL WITH MHD CONVERSION TOKAMAK

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	181.8	1357.0	104.3	73.0	182.4	2490
WEIGHT	377.0	7463.5	1372.2	960.5	1094.6	11268
COST	150.2	149.3	121.7	85.2	27.4	

NEUTRON WALL LOADING(PWN) 3.742
MASS POWER DENSITY,MPD(KWe/TONNE) 106.50

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	238.5	
REACTOR BLDG. AND HOT CELLS		198.2
OTHER STRUCTURES AND IMPROV.		40.2
REACTOR PLANT EQUIPMENT	627.5	
SHIELD		149.3
COILS		207.0
STRUCTURE		27.4
AUX. HEATER		45.0

TOTAL NUCLEAR ISLAND		428.6
HEAT TRANSFER AND TRANSPORT		8.0
OTHER REACT PLANT EQUIP		190.9
TURBINE PLANT EQUIPMENT	0.0	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	34.9	
MAIN COND. HEAT REJECTION	20.1	

TOTAL DIRECT COST	1047.1	
INDIRECT COSTS	392.7	

TOTAL DIRECT+INDIRECT	1439.8	
CONTINGENCY	216.0	

TOTAL OVERNIGHT COST	1655.8	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		151.71		19.24
OPER AND MAINT		60.70		7.70
FUEL CHARGE BREAKDOWN				
BLANKETS	54.14		6.87	
LIMITERS	2.02		0.26	
AUXILIARY HEAT	0.00		0.00	
OTHER FUEL	2.43		0.31	
WASTE DISPOSAL	7.88		1.00	
	-------		------	
TOTAL FUEL COST		66.47		8.43
		-------		-------
TOTAL COST		278.88		35.37

Fig. B.7 (continued)

ORNL–DWG 88–4378 ETD (PART A)

V FIRST WALL D-He3 FUELED TOKAMAK
02-25-1988

ADV-FUEL ADV-FUEL ADV-FUEL ADV-FUEL ADV-FUEL

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.120		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	3.6		
PLASMA ELLIPTICITY(ELLIP)	2.200		
MAXIMUM FIELD IN COIL(BMAX)	16.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.25	0.50	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.05	0.05	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.25	0.50	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	60.481		
NUMBER OF ITERATIONS(NIT)	5		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.474	0.016	0.393
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	%1115994	2.0343	
PLASMA RADIUS(AP)	2.378		
MAJOR RADIUS(RO)	8.560		
TOROIDAL FIELD IN PLASMA(BO)	%10.118		
BETA RATIO(BRATIO)	0.632		
MEAN PLASMA RADIUS(ABAR)	3.527		
NEUTRON WALL LOADING(PWN)	0.091		
PLANT AVAILABILITY(FAV)	0.750		
CURRENT DRIVE(CURRD)	72.181		
FIRST WALL AREA,M^2(AWALL)	1510.5		
ALPHA POWER,MWT(PALPHA)	3132.7		
NEUTRON POWER,MWT(PNEUT)	125.3		
FUSION POWER,MWT(PFUS)	3258.1		
NUCLEAR POWER,MWT(PNUC)	3270.6		
AUXILLIARY POWER,MWe(PAUX)	0.0		
TOTAL THERMAL POWER,MWT(PTH)	3270.6		
AVAILABLE THERMAL POWER,MWT(PTAV)	1605.9		
ELECTRIC POWER(PEL)	1200.0		
RECIRC. POWER FRACTION	0.03		
SAFETY FACTOR	1.746		

Fig. B.8. Output for V-DHe$_3$/TOK.

ORNL-DWG 88-4378 ETD (PART B)

V FIRST WALL D-He3 FUELED TOKAMAK

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	612.2	845.8	343.8	240.7	321.6	4907
WEIGHT	1836.5	4652.0	6399.0	4479.3	1929.6	19296
COST	193.9	93.0	513.9	359.7	48.2	

NEUTRON WALL LOADING(PWN) 0.091
MASS POWER DENSITY,MPD(KWe/TONNE) 62.19

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	351.0	
REACTOR BLDG. AND HOT CELLS		311.7
OTHER STRUCTURES AND IMPROV.		39.4
REACTOR PLANT EQUIPMENT	1415.8	
BLANKET		193.9
SHIELD		93.0
COILS		873.6
STRUCTURE		48.2
AUX. HEATER		45.0

TOTAL NUCLEAR ISLAND		1253.8
HEAT TRANSFER AND TRANSPORT		21.0
OTHER REACT PLANT EQUIP		140.9
TURBINE PLANT EQUIPMENT	164.5	
ELECTRIC PLANT EQUIPMENT	124.9	
MISCELL. PLANT EQUIPMENT	34.4	
MAIN COND. HEAT REJECTION	19.1	

TOTAL DIRECT COST	2114.7	
INDIRECT COSTS	793.0	

TOTAL DIRECT+INDIRECT	2907.7	
CONTINGENCY	436.2	

TOTAL OVERNIGHT COST	3343.8	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		306.38		38.86
OPER AND MAINT		40.50		5.14
FUEL CHARGE BREAKDOWN				
BLANKETS	0.00		0.00	
LIMITERS	6.21		0.79	
AUXILIARY HEAT	0.00		0.00	
OTHER FUEL	15.81		2.01	
WASTE DISPOSAL	7.88		1.00	
	-------		------	
TOTAL FUEL COST		29.91		3.79
		-------		-------
TOTAL COST		376.79		47.79

Fig. B.8 (continued)

ORNL--DWG 88-4379 ETD (PART A)

RAF FIRST WALL Li COOLED Be/Th METAL HYBRID
02-25-1988

LIBE-HYB LIBE-HYB LIBE-HYB LIBE-HYB LIBE-HYB

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.100		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	4.0		
PLASMA ELLIPTICITY(ELLIP)	2.500		
MAXIMUM FIELD IN COIL(BMAX)	10.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.76	0.76	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.10	0.10	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.53	0.53	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	20.446		
NUMBER OF ITERATIONS(NIT)	21		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.595	0.022	0.303
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	6428	2.2598	
PLASMA RADIUS(AP)	1.248		
MAJOR RADIUS(RO)	4.994		
TOROIDAL FIELD IN PLASMA(BO)	4.266		
BETA RATIO(BRATIO)	0.427		
MEAN PLASMA RADIUS(ABAR)	1.974		
NEUTRON WALL LOADING(PWN)	2.639		
PLANT AVAILABILITY(FAV)	0.650		
CURRENT DRIVE(CURRD)	13.313		
FIRST WALL AREA,M^2(AWALL)	515.4		
ALPHA POWER,MWT(PALPHA)	340.0		
NEUTRON POWER,MWT(PNEUT)	1360.0		
FUSION POWER,MWT(PFUS)	1700.0		
NUCLEAR POWER,MWT(PNUC)	3658.4		
AUXILLIARY POWER,MWe(PAUX)	66.6		
TOTAL THERMAL POWER,MWT(PTH)	3724.9		
AVAILABLE THERMAL POWER,MWT(PTAV)	3603.0		
ELECTRIC POWER(PEL)	1200.1		
RECIRC. POWER FRACTION	0.11		
SAFETY FACTOR	2.268		

Fig. B.9. Output for RAF-Li/HYB.

ORNL–DWG 88–4379 ETD (PART B)

RAF FIRST WALL Li COOLED Be/Th METAL HYBRID

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	417.0	460.8	156.2	39.1	97.6	1635
WEIGHT	1259.3	3225.6	1234.3	308.6	585.9	6614
COST	137.7	64.5	111.1	27.8	15.0	

NEUTRON WALL LOADING(PWN)	2.639
MASS POWER DENSITY,MPD(KWe/TONNE)	181.46
REPROCESSING PLANT THROUGHPUT,Mg/YEAR	319.3

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	264.9	
REACTOR BLDG. AND HOT CELLS		149.8
OTHER STRUCTURES AND IMPROV.		115.2
REACTOR PLANT EQUIPMENT	725.4	
SHIELD		64.5
COILS		138.9
STRUCTURE		15.0
AUX. HEATER		112.3

TOTAL NUCLEAR ISLAND		330.7
HEAT TRANSFER AND TRANSPORT		207.0
OTHER REACT PLANT EQUIP		187.7
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	46.0	
MAIN COND. HEAT REJECTION	53.1	
FISSILE FUEL RECOVERY PLANT	531.9	

TOTAL DIRECT COST	1978.3	
INDIRECT COSTS	741.8	

TOTAL DIRECT+INDIRECT	2720.1	
CONTINGENCY	408.0	

TOTAL OVERNIGHT COST	3128.1	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		286.62		41.94
OPER AND MAINT		%108.96		15.95
FUEL CHARGE BREAKDOWN				
BLANKETS	22.92		3.35	
LIMITERS	2.31		0.34	
AUXILIARY HEAT	4.81		0.70	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		39.31		5.75
		-------		-------
TOTAL COST		434.89		63.64

Fig. B.9 (continued)

ORNL–DWG 88–4380 ETD (PART A)

SS FIRST WALL He COOLED MOLTEN SALT HYBRID
02-25-1988

MS-HYB MS-HYB MS-HYB MS-HYB MS-HYB

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.100		
ASPECT RATIO OF TORUS(R/a)(ASPECT)	4.0		
PLASMA ELLIPTICITY(ELLIP)	2.500		
MAXIMUM FIELD IN COIL(BMAX)	10.000		
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.70		
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.80	0.80	
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.10	0.10	
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.46	0.46	
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	20.446		
NUMBER OF ITERATIONS(NIT)	20		
THERMAL DIFFUSIVITY(M^2/S) CHIMAX,CHIEXP	0.672	0.020	0.295
B4RAB(T^4*M^3) AND DENSITY(1/E+20)	7963	2.4115	
PLASMA RADIUS(AP)	1.284		
MAJOR RADIUS(RO)	5.136		
TOROIDAL FIELD IN PLASMA(BO)	4.407		
BETA RATIO(BRATIO)	0.441		
MEAN PLASMA RADIUS(ABAR)	2.030		
NEUTRON WALL LOADING(PWN)	3.091		
PLANT AVAILABILITY(FAV)	0.650		
CURRENT DRIVE(CURRD)	14.144		
FIRST WALL AREA,M^2(AWALL)	545.1		
ALPHA POWER,MWT(PALPHA)	421.2		
NEUTRON POWER,MWT(PNEUT)	1684.8		
FUSION POWER,MWT(PFUS)	2106.0		
NUCLEAR POWER,MWT(PNUC)	3453.9		
AUXILLIARY POWER,MWe(PAUX)	70.7		
TOTAL THERMAL POWER,MWT(PTH)	3524.6		
AVAILABLE THERMAL POWER,MWT(PTAV)	3377.0		
ELECTRIC POWER(PEL)	1200.0		
RECIRC. POWER FRACTION	0.13		
SAFETY FACTOR	2.268		

Fig. B.10. Output for SS-He/HYB.

ORNL–DWG 88–4380 ETD (PART B)

SS FIRST WALL He COOLED MOLTEN SALT HYBRID

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	465.7	419.8	167.2	41.8	104.5	1704
WEIGHT	1038.6	2938.9	1320.6	330.2	626.9	6255
COST	193.6	58.8	118.9	29.7	16.0	

NEUTRON WALL LOADING(PWN) 3.091
MASS POWER DENSITY,MPD(KWe/TONNE) 191.84
REPROCESSING PLANT THROUGHPUT,Mg/YEAR 1411.4

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	267.1	
REACTOR BLDG. AND HOT CELLS		153.9
OTHER STRUCTURES AND IMPROV.		113.1
REACTOR PLANT EQUIPMENT	693.3	
SHIELD		58.8
COILS		148.6
STRUCTURE		16.0
AUX. HEATER		119.3

TOTAL NUCLEAR ISLAND		342.7
HEAT TRANSFER AND TRANSPORT		166.9
OTHER REACT PLANT EQUIP		183.7
TURBINE PLANT EQUIPMENT	230.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	45.3	
MAIN COND. HEAT REJECTION	49.7	
FISSILE FUEL RECOVERY PLANT	199.0	

TOTAL DIRECT COST	1611.3	
INDIRECT COSTS	604.2	

TOTAL DIRECT+INDIRECT	2215.5	
CONTINGENCY	332.3	

TOTAL OVERNIGHT COST	2547.8	

***** POWER GENERATION COST *****

	ANNUAL COSTS (MILLIONS 1986 $)		LEVELIZED POWER COST (1986 MILLS/KWH)	
CAPITAL INVESTMENT		233.45		34.17
OPER AND MAINT		74.36		10.88
FUEL CHARGE BREAKDOWN				
BLANKETS	50.35		7.37	
LIMITERS	2.87		0.42	
AUXILIARY HEAT	11.17		1.63	
OTHER FUEL	2.43		0.35	
WASTE DISPOSAL	6.83		1.00	
	-------		------	
TOTAL FUEL COST		73.64		10.78
		-------		-------
TOTAL COST		381.45		55.83

Fig. B.10 (continued)

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