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A STANDARD METHOD FOR ECONOMIC ANALYSES OF INERTIAL CONFINEMENT FUSION POWER PLANTS

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ABSTRACT

A standard method for calculating the total capital cost and the cost of electricity for a typical inertial confinement fusion electric power plant has been developed. A standard code of accounts at the two-digit level is given for the factors making up the total capital cost of the power plant. Equations are given for calculating the indirect capital costs, the project contingency, and the time-related costs. Expressions for calculating the fixed charge rate, which is necessary to determine the cost of electricity, are also described Default parameters are given to define a reference case for comparative economic analyses.

INTRODUCTION

Currently, a variety of methods are being used to calculate and report the capital cost and the cost of electricity (COE) in economic studies of inertial confinement fusion (ICF) electric power plants. A standard method for economic analyses of ICF power plants is presented in this paper. The method is based on the procedures used in comparative studies of nuclear and fossil power plants as described in Ref. 1. The purpose of standardizing the method is to facilitate consistent economic comparisons. A set of default parameters is given in order to define a base case for relative comparisons. It is not intended, however, to exclude the investigation of concepts, approaches, or situations that may differ from the base case. Therefore, the description of the method is complete enough to allow one to evaluate the total capital cost and the COE for other conditions.

COST OF ELECTRICITY

The cost of electricity is given by,

$$COE = \frac{R(TCC) + M + F}{0.0876\, \alpha\, P_n} \quad (¢/kW_e h) \quad , \qquad (1)$$

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where

R = annual fixed charge rate (yr^{-1}),
TCC = total capital cost of the plant (\$M),
M = annual operation and maintenance cost (\$M),
F = annual fuel cycle cost (\$M),
α = availability factor (fraction), and
P_n = total net power of the plant (MW_e).

Each of the terms in this equation will be considered below. We begin with the total capital cost.

TOTAL CAPITAL COST

The total capital cost (TCC) of the ICF power plant is the sum of the direct capital costs, the indirect capital costs, the project contingency, and the time-related costs.

Direct Capital Costs

The two-digit code of accounts for ICF direct capital costs is essentially the same as that being used for fission and coal plants.[1,2] The only difference is that additional accounts are included for the driver equipment and the target factory equipment. The direct capital cost accounts are:

20 Land and land rights
21 Structures and improvements
22 Reactor plant equipment
23 Turbine plant equipment
24 Electric plant equipment
25 Miscellaneous plant equipment
26 Main heat rejection system
27 Driver equipment
28 Target factory equipment

A detailed description of typical components included in accounts 21 - 26 is given in Ref. 3. Note that the the driver and target factory structures are included in account 21 along with the other plant structures. The sum of accounts 20 - 28 is the total direct cost (TDC).

$$TDC = \sum_{i=20}^{28} C_i \quad , \qquad (2)$$

where C_i = direct capital cost of account i.

Indirect Capital Costs

The code of accounts for indirect capital costs also follows current industry practice.[1,2] Owner's costs, which are not included in the Energy Economic Data Base (EEDB)[2,3] but are included in the Nuclear Energy Cost Data Base (NECDB),[1] have been assigned account number 94. The indirect costs are calculated as fractions of the total direct cost.

91 Construction services

$$C_{91} = f_{91}\ TDC \quad . \tag{3}$$

92 Home office engineering and services

$$C_{92} = f_{92}\ TDC \quad . \tag{4}$$

93 Field office engineering and services

$$C_{93} = f_{93}\ TDC \quad . \tag{5}$$

94 Owner's costs

$$C_{94} = f_{94}\ TDC \quad . \tag{6}$$

The sum of accounts 91 - 94 is the total indirect cost (TIC).

$$TIC = TDC\ (f_{91} + f_{92} + f_{93} + f_{94}) \quad . \tag{7}$$

Project Contingency

A project contingency is included as account 95. It is calculated as a fraction of the sum of the direct plus indirect costs.

95 Project Contingency

$$C_{95} = f_{95}\ (TDC + TIC) \quad . \tag{8}$$

Overnight Construction Cost

The so called "total overnight construction cost" (TOC) is the sum of accounts 20 - 95 and is given by

$$TOC = (TDC + TIC)\ (1 + f_{95}) \quad . \tag{9}$$

Current and Constant Dollar Analyses

Once the TOC is determine there are two different ways of expressing the total capital cost and the COE: in current dollars or in constant dollars. In a current dollar analysis, the buying power of the dollar changes with time, while in a constant dollar analysis, the buying power of the dollar remains constant with time and is equal to that of the reference year's dollar. The distinction is explained in more detail in Ref. 1. Levelized current dollar and constant dollar COEs are simply different ways of expressing a figure of merit for the power plant.

Time Related Costs for a Current Dollar Analysis

Accounts are included for escalation and interest during construction. These are expressed as fractions of the total overnight cost.

96 Escalation During Construction

$$C_{96} = f_{EDC}\ TOC \quad . \tag{10}$$

The factor f_{EDC} is given by

$$f_{EDC} = (1 + e)^{0.6\tau} - 1 \quad , \tag{11}$$

where e is the escalation rate, and τ is the construction period in years.

97 Interest During Construction

$$C_{97} = f_{IDC}\ TOC \quad . \tag{12}$$

The factor f_{IDC} is given by

$$f_{IDC} = (1 + e)^{0.6\tau}\ [(1 + x)^{0.4\tau} - 1] \quad , \tag{13}$$

where x is the effective after-tax cost of money. (The after-tax cost of money is discussed later in the calculation of the fixed charge rate.) In the previous two equations it is assumed that the reference year (t_0), in which the cost estimate is made, corresponds to the start of construction. This simple formula gives results which agree closely with the results published by Phung[4] for an S-shaped spending curve that has 50% of the expense paid out at 60% of the construction period. The total capital cost is then given by

$$TCC = TOC\ (1 + f_{EDC} + f_{IDC}) \quad . \tag{14}$$

Substituting Eqs. (11) and (13), the total capital cost can be expressed as,

$$TCC = TOC\ (1 + e)^{0.6\tau}\ (1 + x)^{0.4\tau} \quad . \tag{15}$$

If TOC is in reference year dollars, then TCC will be in dollars of the year of commercial operation, i.e., $t_0 + \tau$.

Time Related Costs for a Constant Dollar Analysis

In a constant dollar analysis, the purchasing power of the dollar remains constant. In this case the real escalation rate,

$$e_r = (1 + e)/(1 + i) - 1 \quad , \tag{16}$$

is used in place of e in Eqs. (11), (13), and (15). Likewise, the real cost of money,

$$x_r = (1 + x)/(1 + i) - 1 \quad , \tag{17}$$

is used in place of x in Eqs. (13) and (15). In the above equations, i is the general inflation rate.

For the constant dollar analysis, the total capital cost is

$$TCC = TOC\ (1 + e_r)^{0.6\tau}\ (1 + x_r)^{0.4\tau} \quad . \tag{18}$$

Note that if the power plant costs escalate at the same rate as general inflation, then the real escalation rate is zero. In this case,

$f_{EDC} = 0$, and $TCC = TOC(1 + x_r)^{0.4\tau}$ for the constant dollar analysis.

FIXED CHARGE RATE

The fixed charge rate (R) is the annual equivalent cost (per dollar of capital investment) of the revenue requirements which are directly related to the capital investment. It includes return on the investment, return of the investment, income taxes arising from the investment, property taxes, and interim replacement costs. We first calculate the current dollar fixed charge rate and then calculate the constant dollar fixed charge rate.

Current Dollar Fixed Charge Rate

The current dollar fixed charge rate can be calculated from the following expression;[1,5]

$$R = \frac{C\,k}{(1 - t)} - \frac{t\,d}{(1 - t)} + t_p + r \quad , \tag{19}$$

where C = capital recovery factor,
k = adjustment for investment tax credit,
t = effective income tax rate,
d = levelized tax depreciation,
t_p = property tax rate, and
r = levelized interim replacement cost.

Before defining the terms in Eq. (19) in more detail, we must define the effective after-tax cost of money.

Effective Cost of Money

The effective after-tax cost of money (x) accounts for the fact that investment capital is raised from a variety of sources, and the interest paid on debt financing is tax deductible. It is calculated from[1,5]

$$x = i_c f_c + i_p f_p + (1 - t) i_d f_d \quad , \tag{20}$$

where i_c = rate of return on common stock,
f_c = fraction of capital from common stock,
i_p = rate of return on preferred stock,
f_p = fraction of capital from preferred stock,
i_d = interest rate on debt, and
f_d = fraction of capital from debt.

Capital Recovery Factor

The capital recovery factor (C) converts a present sum into a uniform series of payments (just like a mortgage at a fixed rate). The capital recovery factor is a function of the cost of money and the period over which the investment must be paid off. It is calculated from[1,5]

$$C(x,N) = \frac{x(1 + x)^N}{(1 + x)^N - 1} = \left[\sum_{n=1}^{N} \frac{1}{(1 + x)^n}\right]^{-1} \tag{21}$$

where x = effective after-tax annual cost of money, and
N = plant life in years.

Investment Tax Credit

The adjustment factor for the investment tax credit is given by

$$k = 1 - \frac{f\, r_{itc}}{(1 + x)} \quad , \qquad (22)$$

where f = the fraction of the total capital cost that is depreciable for tax purposes, and
r_{itc} = investment tax credit rate.

The credit is received at the end of the first year of operation. The factor of $(1 + x)$ in the denominator gives its present value at the begining of operation. The factor f accounts for the fact that interest during construction is not depreciable for tax purposes. From Eqs. (10) through (15), it can be shown that f is given by

$$f = (1 + x)^{-0.4\tau} \quad . \qquad (23)$$

Effective Income Tax Rate

The income tax rate is the combined state and federal income tax. It is calculated as

$$t = t_s + t_f(1 - t_s) \quad , \qquad (24)$$

where t_s = state income tax rate, and
t_f = federal icome tax rate.

Annual Depreciation Expense

The annual equivalent tax depreciation expense is calculated from

$$d = C(x,N) \sum \frac{f\, d(n)}{(1 + x)^n} \quad . \qquad (25)$$

where $d(n)$ is the tax depreciation deduction fraction in year n. The fractions $d(n)$ for nuclear plants[1] are given in Table 1. Note that for tax purposes, the power plant, which has an expected service life of 30 years, is fully depreciated in 10 years.

Property Tax

We assume a property tax rate of 2% and assume that it does not change over the life of the plant. Therefore, property taxes do not change in current year dollars. In constant year dollars they become less and less each year.

$$t_p = 0.02 \quad . \qquad (26)$$

Table 1. Values for d(n) for use in Eq. (25).

Year n	10-yr property nuclear
1	0.08
2	0.14
3	0.12
4	0.10
5	0.10
6	0.10
7	0.09
8	0.09
9	0.09
10	0.09

Interim Replacement Costs

Interim replacement costs are an assigned fraction of the capital cost for the general replacement of plant components that wear out during the life of the plant. The costs of scheduled replacements of major components, such as the first wall of the reactor, are not included in the interim replacement allowance. These costs should be treated as an O&M expenses. The interim replacement cost is calculated as follows

$$r = r_1 \, C(x,N)/C(x_r,N) \quad , \tag{27}$$

where r_1 is the estimate of the interim replacement cost for the first year of operation, expressed as a fraction of the total capital cost. We have assumed that the interim replacement costs escalate at the same rate as general inflation. The ratio of the two C values is a levelizing factor for the replacement costs which increase over the operating life of the plant.

Constant Dollar Fixed Charge Rate

For a constant dollar analysis, the fixed charge rate must be adjusted to reflect the real cost of money; i.e., the inflation-adjusted cost of money. The constant dollar fixed charge rate is given by[4]

$$R_0 = R \, C(x_r,N)/C(x,N) \quad , \tag{28}$$

where R = current dollar fixed charge rate from Eq. (19),
C = capital recovery factor from Eq. (21), and
x_r = real cost of money from Eq. (17).

Note that this adjustment also accounts for the fact that payments that do not change with time, such as the annual property tax, are decreasing in reference year dollars.

OPERATION AND MAINTENANCE COSTS

The levelized O&M cost is calculated from

$$M = C(x,N) \sum_{n=1}^{N} \frac{M(n)}{(1 + x)^n} \quad . \tag{29}$$

where M(n) is the O&M cost in year n and the summation is over the life of the plant. If the annual O&M cost is M_0 in reference year dollars and increases at the same rate as general inflation, then Eq. (29) can be rewritten as

$$M = C(x,N) \, M_0 \, (1 + i)^\tau \sum_{n=1}^{N} \frac{(1 + i)^n}{(1 + x)^n} \quad . \tag{30}$$

Then from the definition of the capital recovery factor (Eq. 21) and the real cost of money (Eq. 17), this can be rewritten as

$$M = M_0 \, (1+i)^\tau \, C(x,N)/C(x_r,N) \quad . \tag{31}$$

The first multiplier inflates the O&M cost from reference year dollars (i.e., the year that construction starts) to dollars in the year of initial commercial operation. The second multiplier (i.e., the ratio of the two C values) is a levelizing factor for the O&M cost which is increasing over the N year life of the plant. Under these assumptions, the levelized O&M cost for a constant dollar analysis is equal to M_0, the O&M cost in reference year dollars.

FUEL COSTS

The constant and current dollar levelized fuel costs are treated in the same manner as the O&M costs. If the fuel cost in reference year dollars is F_0, and the costs escalate at the same rate as general inflation, then the constant dollar fuel cost is also F_0. The current dollar fuel cost is calculated from the reference year cost by

$$F = F_0\,(1 + i)^{\tau}\,C(x,N)/C(x_T,N) \quad . \qquad (32)$$

We propose that only consumable target materials be included in the fuel costs.

BASE CASE ECONOMIC PARAMETERS

The recommended defaults for the economic parameters are listed in Table 2. The return on investment and the capital structure, as well as the inflation rate and tax rates are all taken from Ref. 1. The indirect cost factors are midway between the values for coal and the values for nuclear plants with the best experience in holding down costs. The values for typical fission plants are significantly higher. A comparison of these factors is given in Appendix I.

SAMPLE CALCULATION

The following is a sample calculation of the cost of electricity for a 1000 MW_e (net) power plant with an assumed direct capital cost of one billion (1985 dollars) and a plant availability factor of 70%. The default values listed in Table 2 are used.

Current Dollar Case

First find the total capital cost. From Eq. (9) the overnight construction cost is

$$TOC = 1000(1.0 + 0.52)(1.1) = 1672 \text{ M } (1985\ \$) \quad .$$

Before we can calculate the escalation and interest during construction, the effective after-tax cost of money must be determined from Eq. (20).

$$x = 0.14(0.38) + 0.09(0.12) + (1 - 0.48)(0.10)(0.5) = 0.090 \quad .$$

The escalation during construction factor (Eq. 11) is

$$f_{EDC} = (1.06)^{4.8} - 1 = 0.323 \quad .$$

Table 2. Base case values for the economic parameters.

Rates of return on	
Common stock	i_c = 14%
Preferred stock	i_p = 9%
Debt	i_d = 10%
Fraction of capital from	
Common stock	f_c = 38%
Preferred stock	f_p = 12%
Debt	f_d = 50%
General inflation rate	i = 6%
Escalation rate (for all items)	e = 6%
State income tax rate	t_s = 4%
Federal income tax rate	t_f = 46%
Effective income tax rate	t = 48%
Property tax rate	t_p = 2%
Interim replacement rate	r_l = 0.5%
Investment tax credit	f_{itc} = 8%
Power plant life	N = 30 y
Construction period	τ = 8 y
Indirect cost factors	
Construction services	f_{91} = 0.20
Home office engineering and services	f_{92} = 0.15
Field office engineering and services	f_{93} = 0.10
Owner's cost	f_{94} = 0.07
Project contingency factor	f_{95} = 0.10

The interest during construction factor (Eq. 13) is

$$f_{IDC} = (1.06)^{4.8}\ [(1.090)^{3.2} - 1] = 0.420 \quad .$$

Therefore, from Eq. (14), the total capital cost is

$$TCC = 1672(1.743) = 2914 \text{ M } (1993 \$) \quad .$$

Next calculate the fixed charge rate. The capital recovery factor at 9.0% for a 30 year plant life is found from Eq. (21).

$$C(0.090,30) = \frac{0.090(1.090)^{30}}{(1.090)^{30} - 1} = 0.0973$$

The fraction of the initial investment that is depreciable (Eq. 23) is

$$f = (1.090)^{-3.2} = 0.759 \quad .$$

The investment tax credit adjustment factor, from Eq. (22), is then

$$k = 1 - [(0.759)(0.08)/(1.09)] = 0.944 \quad .$$

The levelized depreciation, from Eq. (25) and table I, is

$$d = (0.0973)(0.759)(0.6531) = 0.0482 \quad .$$

To find the levelized interim replacement cost (Eq. 27), we must first calculate the real cost of money from Eq. (17),

$$x_r = 1.090/1.060 - 1 = 0.0283 \quad ,$$

and the levelizing factor,

$$C(x,N)/C(x_r,N) = 0.0973/0.0499 = 1.95 \quad .$$

Therefore, the levelized interim replacement cost is

$$r = 0.005(1.95) = 0.0098 \quad .$$

Then with a property tax rate of 2%, the current dollar fixed charge rate, from Eq. (19), becomes

$$R = 0.0973(0.944)/0.52 - 0.48(0.0482)/0.52 + 0.020 + 0.010 = 0.162 \quad .$$

Thus the current dollar fixed charge rate is 16.2%.

We assume that the reference year O&M cost is $55 M, which is consistent with O&M costs for nuclear and fossil plants.[1] We also assume that the O&M cost escalates at the same rate as general inflation. The constant dollar levelized O&M cost is, therefore, equal to the reference year O&M cost,

$$M_0 = 55 \text{ M } (1985 \$) \quad .$$

The current dollar levelized O&M cost is calculated from Eq. (31). We must first calculate the real cost of money from Eq. (17) and the levelizing factor.

$$x_r = 1.090/1.060 - 1 = 0.0283 \quad .$$

The levelizing factor is

$$C(x,N)/C(x_r,N) = 0.0973/0.0499 = 1.95 \quad .$$

Therefore, the current dollar levelized O&M cost is

$$M = 55(1.06)^8(1.95) = 171 \text{ M} \quad .$$

For this example, we assume that the annual fuel costs are negligible. Then

$$F = 0 \quad .$$

The cost of electricity can now be calculated from Eq. (1).

$$COE = \frac{0.162(2914) + 171 + 0}{0.0876(1000)(0.7)} = 10.49 \text{ ¢/kW}_e\text{h} \quad .$$

Constant Dollar Case

For the constant dollar analysis the total overnight construction cost is the same as before.

$$TOC = 1672 \text{ M } (1985 \$) \quad .$$

Since the escalation rate is equal to the general inflation rate $e_r = 0$, and the escalation during construction factor is zero (see Eqs. 16 and 11). The interest during construction factor is calculated from Eq. (13) using the real cost of money (x_r) in place of x.

$$f_{IDC} = (1.0283)^{3.2} - 1 = 0.093 \quad .$$

Therefore, the total capital cost is

$$TCC = 1672(1.093) = 1828 \text{ M } (1985 \$) \quad .$$

The constant dollar fixed charge rate is calculated from Eq. (28) using the results in the current dollar section.

$$R_0 = 0.162(0.0499)/0.0973 = 0.083 = 8.3\% \quad .$$

The O&M cost does not change from the reference year cost

$$M_0 = 55 \text{ M} \quad .$$

The constant 1985 dollar cost of electricity is thus found to be

$$COE_0 = \frac{0.083(1828) + 55 + 0}{0.0876(1000)(0.7)} = 3.37 \text{ ¢/kW}_e\text{h} \quad .$$

The results of the example calculation are listed in Table 3.

Table 3. Summary of sample COE calculation

	Current $		Constant $
Net power, MW_e		1000	
Availability factor, %		70	
Total direct cost, $M		1000	
Construction services and equipment, $M		200	
Home office engineering and services, $M		150	
Field office engineering and services, $M		100	
Owner's cost, $M		70	
Project contingency, $M		152	
Total overnight cost, $M		1672	
Escalation during Construction, $M	540		0
Interest during construction, $M	702		156
Total capital cost, $M	2914		1828
Fixed charge rate, %	16.2		8.3
Levelized O&M cost, $M	171		55
Levelized fuel cost, $M	0		0
Cost of Electricity, ¢/kW_eh	10.49		3.37

SUMMARY

A standard metnod for calculating the total capital cost and the cost of electricity for a typical inertial confinement fusion electric power plant has been presented. Using the default parameters recommended in Table 2, we find that the total capital cost is 1.83 times the direct capital cost for a constant dollar analysis. This factor includes all indirect costs, a project contingency, and time-related costs (interest during construction). The constant dollar fixed charge rate is 8.3%. All the equations needed to derive these factors, as well as the corresponding factors for a current dollar analysis, are given. This allows one to investigated the effects of changes in the assumed default parameters. The default parameters should be used as a base case in economic analyses of ICF power plants to facilitate consistent comparison of various reactor/driver options as well as comparisons with conventional power plants such as fission and coal. It is for this purpose that the standard method for economic analyses of ICF power plants has been proposed in this paper.

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APPENDIX I. COMPARISON OF INDIRECT COST FACTORS

In Table I.1 the indirect cost factors used for nuclear and coal plants are compared to those proposed for the ICF standard. The ICF standard defaults from Table 2 are shown in the last column. Note that the values selected are midway between the values for nuclear and coal. This is true using either the NECDB or the GCRA data. The NECDB nuclear case corresponds to the EEDB "best experience" case. The average experience case of the EEDB is significantly higher. Also note that the end result for the ICF standard is consistent with those values used by GA Technologies for the Cascade reactor design. Hence, it is felt that the proposed parameters are a good, representative set which will allow consistent comparison with other energy sources. The project contingency (C_{95}) is given as a fraction of the total direct cost so that the tabulated values can simply be added. The ICF case corresponds to a value of $f_{95} = 0.1$.

Table I.1 Comparison of indirect cost factors form several sources.

	NUCLEAR				FOSSIL			FUSION	
	NECDB[1]	GCRA[7]	EEDB[2]	EEDB/B	NECDB	GCRA	EEDB	CASCADE[6]	ICF
TDC	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
f_{91}	0.266	0.172	0.333	0.238	0.144	0.108	0.137	0.148	0.200
f_{92}	0.240	0.188	0.323	0.234	0.056	0.092	0.060	0.155	0.150
f_{93}	0.130	0.078	0.351	0.117	0.044	0.042	0.042	0.067	0.100
Sub-total	1.636	1.438	2.007	1.589	1.244	1.242	1.239	1.370	1.450
f_{94}	0.084	0.144			0.056	0.124		0.137	0.070
$\frac{Acc\ 95}{TDC}$	0.169	0.237			0.133	0.137		0.203	0.152
TOC	1.889	1.819			1.433	1.503		1.710	1.672

Nuclear: NECDB = 1100 MW_e PWR
GCRA = 1800 - 3600 MW_t PWR
EEDB = 1139 MW_e PWR, Median experience
EEDB/B = 1139 MW_e PWR, Best experience

Fossil: NECDB = 550 MW_e Coal
GCRA = 1200 - 2400 MW_t Coal
EEDB = 486 MW_e Coal

Fusion: Cascade = 1670 MW_L, 905 MW_e (gross)

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