# FUSCOST: A PC-Based Menu Driven Program for Economic Analysis of Fusion Facilities

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FUSCOST: A PC-BASED MENU DRIVEN PROGRAM FOR ECONOMIC ANALYSIS OF FUSION FACILITIES

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## Introduction

An economic analysis program for the IBM-PC computer and using BASICA processor will be described. This program is for analysis of fusion facilities, both inertially confined (ICF) and magnetically confined (MFE). The applicable scaling laws and the economic model will be presented here. The program is user-friendly; on-screen menus guide the user and self-explanatory data entry screens with extensive editing capabilities facilitate the data input process. Therefore, the program is very easy to use; after the initial loading the user need only follow the instructions that the program gives. The code will calculate the direct and indirect costs, the total capital cost, the applicable annual costs (operations and maintenance, fuel, electricity) and the cost of electricity produced, if applicable. Currently, the program assumes scaling laws for mature technology; it can still be used for comparison purposes for test reactors. It is intended that this program aid in making economic comparisons and not for detailed costing of an actual facility.

The program consists of several parts. The scaling laws and the economic model are employed in the actual calculations that the user is interested in. The scaling laws calculate the direct cost (in 1986 dollars) of plant equipment, given certain plant parameters (e.g. net electric power or the amount of material in the first wall). The economic model calculates all the other components of the cost (total direct cost of the plant, indirect cost, total capital cost, annual costs-fuel, electricity, operations and maintenance, and the cost of electricity produced, if applicable). These costs can also be escalated to the proper reference year. The inputs to the economic model are user provided and deal with economic assumptions, e.g. the inflation and escalation rate, the cost of money, construction time, etc. The user interface part of the program provides the connection between the user and the calculation part, by facilitating input and presenting the output.

## The Scaling Laws

The scaling laws relate the cost of an account item to a variable in the plant design; e.g. the cost of an ICF laser is related to the energy on target, or the cost of the heat rejection equipment is related to the rejected thermal power. Sometimes different sources will quote different scaling laws. We have attempted to use the most up to date scaling laws; these can be changed in the program if the need arises. The laws will give the costs in 1986 dollars, but there is a provision in the program to express the results in given dollars. The scaling laws come from various sources and from various years; they have been escalated to 1986 levels by employing the prevailing escalation rates in the intervening years. Sources include design reports, papers, private communications and recent compilations of such laws.

MFE Scaling Laws. Most of the MFE scaling laws come from Ref. [1] and are similar to ICF scaling laws in Table 1. Ref. [2] and [3] were used in some parts, notably the direct convertor and related equipment. The cost of the direct convertor is given by: $C_d = 2.25 \cdot P_{todc}^{0.8}$ where $P_{todc}$ = total power into the direct convertor in MW. The cost of the direct convertor power conditioning equipment is: $C_{dcpc} = \eta d_c \times 0.12 \cdot P_{todc}$; both costs are in M$, $\eta d_c$ is direct convertor efficiency.

ICF Scaling Laws. Table 1 presents the ICF scaling laws for a laser driven plant [4], [5]. They are similar for applicable items to the MFE scaling laws. There are some differences, however; the vacuum in a laser driven plant is much softer than that in an MFE facility; the tritium burnup is typically much higher, and hence demands on the fuel system are relaxed; the fuel injectors have to supply much lower velocities in an ICF plant.

KrF Laser Costing [6]. For a system of multiplexed 200 kJ amplifiers and 4 J/cm$^2$ fluence limit, the cost is given by:

$$C_d = \$150M\ E_d^{0.74} \exp(0.024\ w_d)\ \exp[f(E_d)(\tau_{do}/\tau_d - 1)]$$

$E_d$ = driver energy (MJ)

where $w_d$ = rep rate (Hz)

$f(E_d) = 0.05 + 0.001\ E_d$

$\tau_{do}$ = reference pulse length (10 ns)

$\tau_d$ = pulse length.

The cost scales most strongly with driver energy.

Heavy Ion Driver costing [6]. The algorithm for the heavy ion driver assumes that induction technology will be ultimately cheaper than the rf technology. The cost is:

$$C_d = \$680M\ E_d^{0.4} + \$100M\ (N_c N_u - 1)$$

where

$E_d$ = driver energy (MJ)

$N_c$ = number of chambers/power unit

$N_u$ = number of power units.

This relationship takes into account the cost of additional beam transport lines for multiple chambers.

Light Ion Driver Costing [6], [7]. The cost of the light ion beam driver is:

$$C_d = \$50M\ \left(\frac{E_d}{1-0.075\ R}\right)^{0.8}$$

where

$E_d$ = driver energy on target (MJ)
$R$ = chamber radius (m) to the diode.

This relationship accounts for the fact that for a

Table 1. Scaling Laws for ICF Laser Driven Plant

| Account Item | Scaling Law |
|---|---|
| REACTOR EQUIPMENT | |
| 1st wall graphite | \$4520./kg |
| Lead and LiPb | \$4./kg |
| 90% LiPb | \$12/kg |
| Li | \$40/kg |
| 90% Li | \$1200/kg |
| Steel | \$50./kg |
| SiC in tubes | \$950./kg |
| SiC, other fabricated | \$1900./kg |
| Shield concrete | $\$1000/m^3$ |
| Pellet injector | \$0.75M |
| Last mirror shield | \$2.11M |
| Reactor vacuum roots blower (3000 l/s) | \$13.5K/unit |
| Vacuum exhaust duct | \$15.1K/m |
| Exhaust circulation, 1 atm | \$316K |
| Fuel cleanup | \$2.01M |
| $H_2$ isotope separation | \$250.K |
| U storage beds | \$107.K |
| $T_2$ breeding equipment | \$7.2M |
| Cavity gas recycle | \$3.14M |
| Xe inventory | \$10.20/l |
| Radwaste system | $\$1951. * P_{th}$ |
| Fuel storage cryogenics | \$2.71M |
| Fuel storage tank | \$121.K |
| LM* cooling, pumps | $\$27.45M * \dot{m}/3.2E+8$ kg/h |
| LM cooling, SS piping | \$339.K/m |
| LM cooling, heat exchangers | $\$81.2M * P_{th.Pb}/2081$ MW |
| LM cooling, cleanup system | \$7.5/kg coolant |
| LM cooling, tanks, 400 $m^3$ | $\$1433/m^3$ |
| $H_2O$ cooling, pumps 1E+05 kg/hr | \$264.K/unit |
| $H_2O$ cooling, SS piping | \$12.1 K/m |
| $H_2O$ cooling, heat exchangers | $\$31.8M * P_{th,w}/730$ MW |
| $H_2O$ cooling, tanks, 400 $m^3$ | $\$173./m^3$ |
| Auxiliary cooling | $\$0.0049M * P_{th}$ |
| Laser power supply cooling | \$4.5/kWth |
| Instrumentation and control | $\$2.52M * P_{th}^{0.3}$ |
| Maintenance equipment | $\$4.1M * P_{th}^{0.3}$ |

*LM stands for liquid metal.

Table 1. (continued)

| Account Item | Scaling Law |
|---|---|
| LAND | |
| Land and land rights | \$5600/acre |
| BUILDINGS AND SITE | |
| Site improvements | \$15M |
| Reactor building | $\$0.0038M * V^{0.8}$ |
| Concrete work | $\$523/m^3$ |
| $T_2$ treatment building | $\$0.00496M * V^{0.8}$ |
| Control building | $\$0.00182M * V^{0.85}$ |
| Maintenance building | $\$0.0018M * V^{0.7}$ |
| Radwaste building | $\$0.00496M * V^{0.8}$ |
| Administration building | \$1.5M |
| Diesel generator building | \$0.5M |
| Cooling system structures | $\$9.05M * (P_g/1000.)^{0.3}$ |
| Hot cell building | \$7.1M |
| Laser hall, in "Laser equip." | NA |
| Rest of the buildings | \$3.4M |
| HEAT REJECTION PLANT | $\$145K * P_g^{0.8}$ |
| ELECTRICAL PLANT WITHOUT ELECTRIC CONVERSION | |
| Driver power supply | $\$31.7M * P_{in}/100.$ |
| Grounding | \$2.1M |
| Rest | $0.021 * P_{th}$ |
| ELECTRICAL PLANT WITH ELECTIRC CONVERSION | $\$5.7M * P_g^{0.2} * P_{in}^{0.3}$ |
| TURBINE PLANT (IF EXISTS) | $\$0.35M * P_{th}^{0.8}$ |
| MISCELLANEOUS PLANT | $\$5.05M * P_g^{0.3}$ |
| KrF LASER EQUIPMENT | $\$150.M * E_d^{0.7}$ |
| TARGET FACTORY | \$100.M |

$P_{th}$ = thermal power (MW)

$P_g$ = gross electric power (MW)

$P_{in}$ = laser input power, MW

Ed = energy on target, MJ

V = volume ($m^3$)

m = mass flow rate (kg/h)

given energy on target, the energy required at the diode depends on the chamber radius.

Target Factory Equipment [6]. This cost is calculated by:

$$C_{tf} = \$33M \cdot w^{0.6}[(y/y_0)^{0.6} + 2\ (y/y_0)^{0.2}]$$

where $w$ = rep rate in Hz
$y$ = target yield in MJ
$y_0$ = reference target yield (100 MJ).

Additional Considerations in ICF Facilities Costing. There is also an option in the code for a very rough calculation of the facility cost by using the back of the envelope relationships published elsewhere [8], [9]. Basically this option breaks up the facility into the driver, target factory and the "reactor" (including everything else) with a simple scaling relationship to account for each major entity. This option would be used for very rough comparisons. The reactor part cost is given by: $C_R = \$660M \cdot (P_t/1.67)^{0.49}$ where $P_t$ is the thermal power in GW.

## The Economic Model

The economic model takes the direct cost for individual plant equipment and user supplied economic parameters to arrive at the other costs of interest:

Total overnight cost (TOC) = Total direct cost (TDC) + Total indirect cost (TIC)

The TOC is the cost of the facility if built overnight, i.e. without the cost of borrowed money, inflation and escalation taken into account. It is calculated by multiplying the TDC by some factor to account for the project contingency and items of indirect cost: construction cost, home office cost, field office cost and owner's cost.

Total capital cost (TCC) = Total cost of the facility including borrowing the money and time effects.

$$TCC = f(x,e,t_c,TOC)$$

where $e$ = effective escalation rate
$x$ = cost of money (interest rate)
$t_c$ = construction time.

The current dollar TCC (given in dollars of the year at the end of construction) includes effects of inflation as opposed to escalation. The inflation measures the loss in the value of money over time, while escalation is due to a real increase in cost.

The levelized annual cost includes charges for investment return, any fuel cost, any electricity cost and the cost of operations and maintenance (O&M). The investment return is given by $f_{CR} \cdot TCC$ where $f_{CR}$ is the fixed charge rate:

$$f_{CR} = f(s,t,t_p,t_{ci},f_{ir},x,L,e,i,t_c,t_d)$$

where $s$ = salvage fraction at end of life
$t$ = income tax rate
$t_p$ = property tax rate
$t_{ci}$ = investment tax credit rate
$f_{ir}$ = annual interim replacement fraction
$L$ = plant life
$t_c$ = construction time
$t_d$ = depreciation time

and the TCC is given in either constant or current dollars.

The rest of the annual costs are also given in both constant and current dollars. The O&M costs are calculated as a certain fraction of TOC. The fuel cost depends on fusion power and capacity factor (for TBR < 1). The cost of electricity purchased can be significant in ICF facilities and is related to driver efficiency, energy on target and rep rate. Also, a certain fraction of gross electric power (5%) is used to run other plant equipment (e.g. pumps). The current dollar figures give these costs in the dollars of the first year of operation of the facility (assuming it coincides with the end of construction). Special cases (e.g. government owned facility) can be calculated by adjusting certain inputs (in this case the cost of money and tax rates). In addition, a non-linear construction schedule is allowed.

The cost of electricity is arrived at by dividing the levelized annual cost by the total annual amount of electricity produced:

$$COE = (f_{CR} \cdot TCC + AC)/(fav \cdot P_{net}) \cdot C$$

where $P_{net}$ = net electric power output
$AC$ = annual cost
$fav$ = capacity factor.

The economic model parameters and their suggested values are given in Table 2. This generally follows ICF plant recommendations [10].

It should be noted that the MFE economic assumptions are generally milder. If an MFE and an ICF design are compared, the economic assumptions should be consistent (e.g. equal inflation and escalation rates, cost of money, with certain variations possible, e.g. plant construction time). For a more detailed description of the economic model and its parameters, see [10] or [11].

Table 2. Economic Parameters and Suggested Values

| Description | Suggested Value |
|---|---|
| Plant availability if applies | 0.75 |
| Operations and maintenance cost fraction (per year) | 0.03 |
| Salvage fraction | 0.00 |
| 10 year or 15 year TEFRA accelerated tax depreciation | 10 |
| General inflation rate | 0.06 |
| Cost escalation rate, average | 0.06 |
| Construction time in years, up to 12 | 6 |
| Plant life in years | 30 |
| Construction factor, f91 | 0.15 |
| Home office factor, f92 | 0.15 |
| Field office factor, f93 | 0.15 |
| Owner's cost factor, f94 | 0.05 |
| Project contingency factor, f95 | 0.10 |
| Rate of return on common stock | 0.14 |
| Fraction of capital from common stock | 0.40 |
| Rate of return on preferred stock | 0.11 |
| Fraction of capital from preferred stock | 0.10 |
| Interest rate on debt | 0.10 |
| Fraction of capital from debt | 0.50 |
| Total income tax rate | 0.50 |
| Investment tax credit rate | 0.08 |
| Property tax rate | 0.02 |
| Levelized interim replacement cost fraction | 0.01 |
| Reference year of cost | 1986 |

## The Interface Between The User And The Program

The interface between the user and the program is very user friendly which makes it easy to input the data and run the code.

There are two versions of the program: one for the MFE work, and the other for ICF. In the ICF version, one can choose among the three types of drivers: laser, light ion and heavy ion beam. In the MFE version, the choice is between tandem mirrors, tokamaks and "other" configurations, with an option of using advanced fuels (D-He3).

Once the version is selected and the program is loaded, the code will guide the user and ask for proper input. This is accomplished by menu screens and data input screens. The data input screens have extensive editing capability including the possibility of backtracking help screens and skipping ahead. The screens will show the default values from a previous run. The screens for input of economic model variables will also show the suggested values. In addition to the economic parameters discussed above, the user can also input a spending profile (fraction of capital spent in each year during construction). Spending a higher fraction earlier in the construction is beneficial from the economic standpoint.

The program output consists of the total direct cost and the main drivers, total overnight cost, total capital cost, fixed charge rate, annual, O&M costs, fuel costs, electricity costs, the total levelized annual cost and the cost of electricity.

Any number of cases can be run once the program is loaded. While the loading process takes about 30 s there is no delay thereafter.

Some portions of the program were taken from [12].

## Some Assumptions in the Program

In order to limit the number of assumptions for this code, certain options have been eliminated. For instance, there is no provision for an ICF chamber using $Li_2O$ particles as coolant. The coolant fraction in the reactor is assumed to be 1/3 of the total loop coolant inventory. The vacuum system for a laser or light ion driven facility is relatively inexpensive, whereas the one for heavy ion fusion approaches MFE requirements. Multiple chambers and multiple power units are assumed to exist just for the heavy ion driven facility because of the high cost of this driver and chamber rep rate limitations. The additional power units have reduced direct and indirect costs [9]. A target factory may or may not exist on site of an ICF facility; the same is true for electric conversion equipment for either an MFE or ICF facility.

## Conclusions

The computer program FUSCOST offers a flexible and quick way of running economic studies on an IBM-PC compatible using the Microsoft Basic processor. It is well suited for doing parametric studies and economic comparisons of various design alternatives. Up to date scaling laws provide enough accuracy to do this. The economic model input parameters have suggested values shown. Menu screens and input data screens make it easy for the user to input and change the input data. The output is concise and contains the necessary information: the capital cost components, the annual cost components and the cost of electricity.

## Acknowledgment

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