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SAFIRE—A Systems Analysis Code for ICF Reactor Economics

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SAFIRE--A SYSTEMS ANALYSIS CODE FOR ICF REACTOR ECONOMICS

ABSTRACT

The SAFIRE (Systems Analysis for ICF Reactor Economics) code incorporates analytical models for scaling the cost and performance of several inertial confinement fusion reactor concepts for electric power. The code allows us to vary design parameters (e.g., driver energy, chamber pulse rate, net electric power) and evaluate the resulting change in capital cost of the power plant and the busbar cost of electricity. The SAFIRE code can be used to identify the most attractive operating space and to identify those design parameters with the greatest leverage for improving the economics of inertial confinement fusion electric power plants.

1. INTRODUCTION

1.1 OVERVIEW

The economic performance of inertial confinement fusion (ICF) electric power plants is often compared with that of present-day commercial systems by using total capital cost and cost of electricity (COE) as figures of merit. To facilitate this comparison, an ICF system performance and costing model, the SAFIRE code, has been developed. By using SAFIRE, point designs for several ICF reactor concepts and balance of plant (BOP) options can be scaled to different operating conditions. The capital cost and COE are calculated as a function of selected operating conditions.

Because many technologies needed to support an ICF reactor are in early stages of development, it is difficult to make an accurate quantitative assessment of the figures of merit. However, the SAFIRE code can easily accept refinements to the analytic models as they become available. In its present state of development, the SAFIRE code is mainly useful for making consistent comparisons and for identifying plant characteristics with high leverage for improving economics.

The costs of reaction-chamber-related items are normalized to those of the designs or to more recent sources. The BOP items are normalized to the costs given in the Energy Economic Data Base and the Nuclear Energy Cost Data Base.¹⁻³ Consistent with Ref. 3, a reasonable reduction in construction time and overhead is assumed relative to present-day nuclear power plants. The code of major accounts used and the calculations of indirect costs, time-related costs, and the COE follow the methods specified in Ref. 4.

We can investigate a diverse array of scenarios with the SAFIRE code. Besides the various combinations of reaction chamber concepts and drivers, the power plant can be configured in a variety of ways. We can consider multiple chambers with a single BOP and/or multiple reactors with a single driver and target factory. (As used here, a reactor is defined as one or more reaction chambers and the BOP equipment and structures required for producing electric power.) Sharing a single driver and target factory with more than one reactor, and operating at high net electric power help reduce the COE.

Figure 1-1 summarizes the calculations that the SAFIRE code performs to determine the COE for an ICF power plant. The input includes the chamber pulse rate and either the driver energy or target gain. The gain curve, type of chamber, and type of driver are also specified either as input or by the default settings within the code. There are three gain curves for laser drivers that correspond to two current designs and one advanced target design. There are eight gain curves for heavy-ion drivers that correspond to different $r^{3/2}R$ parameters with single- and double-shell targets, where r is the ion beam radius and R is the ion range in the target. The options for the chamber type include Cascade,⁵ HYLIFE,⁶ HIBALL,⁷ EAGLE,⁸ and a dry-wall chamber.^{9,10} The user can select from a KrF-laser, heavy-ion, or light-ion driver. The heavy-ion-beam (HIB) model will soon be updated with the model developed during the Heavy Ion Fusion System Assessment Project.¹¹ Plans are also being made to develop and incorporate a model for an advanced solid-state driver. The number of chambers per reactor unit, the number of units per plant, and the number of drivers and target factories per plant are all input or defaulted at this point. The input also specifies whether or not the code is to converge on a specific net electric power by varying the driver energy.

Using a target-gain vs driver-energy relationship, the code calculates the gain for a given energy (or driver energy for a given gain); this result, combined with the pulse rate and type of chamber, permits the calculation of

Figure 1-1. Summary of calculational steps carried out by the SAFIRE code.

the target yield, fusion power, and thermal power. The thermal power depends on the chamber type because different concepts have different neutron energy multiplication factors.

The size of the chamber is scaled with either the target yield or the thermal power. For example, the radius of the HYLIFE chamber is taken to be proportional to the square root of the target yield. The thickness of the jet array is set based on radiation damage limits and the desired 30-year life of the first structural wall (FSW). The impact stress due to the expanding jet array, and the thermal stress in the first wall are used to calculate the required wall thickness. Knowing the radius and height of the chamber and the wall thickness allows the code to calculate the total structure volume and its cost.

The thermal-to-electric conversion efficiency is calculated based on the maximum coolant temperature from the chamber and the type of power cycle. The liquid-metal-cooled chambers use a Rankine cycle; the Cascade chamber uses a Brayton cycle. With the steam cycle the user has the option of replacing the intermediate loop with a double-wall heat exchanger. This does not affect performance, but has some affect on cost. The algorithms used to calculate steam cycle efficiency are based on numerical fits to the performance data of operating plants. The Brayton cycle efficiency is calculated from an analytical model that uses helium as the working fluid.

The gross electric power can now be calculated from the thermal power and conversion efficiency. To determine the net electric power of the plant, we must first calculate the driver power, pumping power, and auxiliary power requirements of the plant. The driver power is proportional to the driver energy and pulse rate and inversely proportional to the driver efficiency, which is a function of pulse rate. The chamber pumping power depends on the power level and, in the case of HYLIFE, on the pulse rate. The other auxiliary power requirements are taken as a fixed fraction of the gross electric power of the plant.

The direct capital costs of the chamber, BOP buildings and equipment, driver, and target factory are scaled in various ways. The building costs, for example, are a function of the building size, which scales with either electric or thermal power. Likewise, some of the heat transfer and power conversion equipment scales with thermal and some with electrical power. All direct costs fall into one of eight two-digit accounts (see Section 7). The cost algorithms are based on cost studies done in various years. The code

automatically adjusts all costs to a single reference year using inflation factors. The subaccounts under Accounts 21, 22, 24, 25, and 26 have been normalized wherever possible to the Energy Economic Data Base.^{1,2} Some of the cost scaling is extracted from the Nuclear Energy Cost Data Base.³ General industrial experience does not give us sufficient data to specify the fusion-specific subaccounts of Account 22, Reactor Plant Equipment. Therefore, we have relied on the cost estimates given in published design studies of ICF reactor concepts, such as the Cascade final report.⁵

The calculation of the total capital cost of the plant accounts for all indirect and time-related costs. Cost savings for building multiple unit plants are also taken into account. The COE is calculated using the standard method for ICF economic analyses,⁴ and the results are given in both current and constant dollars.

If the user requests a specific net power, the code will search for the driver energy that gives the desired power. In this case, the entire set of calculations is repeated in each iteration. When the problem is completed the code writes output files with varying levels of detail. It also writes a file that shows the order in which subroutines were called and returned, which provides a built-in flowchart for the code.

The algorithms are discussed in the remainder of this document, and the structure of the code is discussed in more detail in Vol. 2 of this report, SAFIRE User's Manual.

1.2 BACKGROUND

The development of SAFIRE began with a code that was developed by TRW and LLNL in 1979 to evaluate the performance of fusion-fission hybrids.⁹ The Bechtel dry-wall hybrid was the original chamber model. The code was later modified to include other hybrid reactor concepts such as the HYLIFE hybrid and some pure-fusion concepts such as HIBALL.

In 1985 we began to update and modify the code. We chose to focus on electric power production and to eliminate the capabilities for evaluating hybrid systems. One of the main tasks was to normalize BOP costs to nuclear industry data. The liquid-metal reactor concepts have been normalized to the costs reported for liquid-metal-breeder reactors in the Energy Economic Data Base^{1,2} and the Nuclear Energy Cost Data Base.³ The Cascade costs were taken directly for the Cascade final report.⁵ GA Technologies' cost

estimate for Cascade also relied on the Energy Economic Data Base. The Krf-laser model is based on recent work at Los Alamos.¹²⁻¹⁴

As part of this work, we have documented the algorithms used in the code and have provided a user's manual (Vol. 2 of this report). We include many of the scaling laws for the BOP systems that were developed by Bechtel National for the original hybrid study but never published.

PART A. TECHNICAL PERFORMANCE SCALING

2. DRIVER EFFICIENCY MODELS

The recirculating power required to run the driver is a function of the driver efficiency η_d . Algorithms for determining η_d for KrF-laser, heavy-ion, and light-ion drivers are described below.

2.1 KrF-LASER DRIVERS

Simple expressions for the cost and efficiency of repetitively pulsed, multiplexed KrF-laser drivers have been developed for commercial fusion applications based on the results of ongoing physics and design studies.¹²⁻¹⁴ Repetitive pulsing reduces KrF-laser system efficiency because of the increased power required to circulate the lasing medium. The circulation power is proportional to the cube of the repetition rate. If we denote the single shot efficiency as η_{d0} , then the driver efficiency scales as

$$\eta_d = \frac{\eta_{d0}}{1 + \left(\frac{\eta_{d0} P_{c0}}{E_{d0} R_d} \right) \left(\frac{R_d}{R_{d0}} \right)^3} \quad (2-1)$$

where

P_{d0} = reference circulation power ($1.74 \times 10^{-3} \text{ MW}_e$),

R_{d0} = reference repetition rate (1 Hz),

E_{d0} = reference driver energy (1 MJ),

R_d = repetition rate (Hz).

The reference values listed above are taken from Ref. 14. The single-shot driver efficiency listed there is 9.1%. This value results from an intrinsic efficiency of 14.6%, a 75% pulsed-power efficiency, a 94.2% power-utilization factor, a 3% laser loss from unpumped regions of the medium, a 2% loss due to windows, an amplifier fill factor of 97.4%, and a 5% beam loss during reactor vessel transport. The repetition rate dependence of Eq. (2-1) is shown in Fig. 2-1.

Figure 2-1. KrF-laser efficiency vs repetition rate.¹⁴

2.2 HEAVY-ION DRIVERS

The efficiency of a heavy-ion driver is a function of repetition rate because some of the subsystems will operate continuously while others are responsive to the duty cycle. The scaling used here is¹⁵

$$\eta_d = \eta_{d0} R_d / (\eta_{d0} + R_d) \quad (2-2)$$

where η_{d0} is the efficiency for 100% duty cycle (25%), and R_d is the repetition rate (Hz). The above expression indicates a noticeable penalty in efficiency for repetition rates below 1 Hz. At repetition rates above 4 Hz, the efficiency approaches the asymptotic value η_{d0} . No distinction is made in calculating the efficiency of a radio-frequency (rf) vs induction device.

2.3 LIGHT-ION DRIVERS

Light-ion drivers are assumed to be of the pulsed power type.¹⁶ The algorithm for calculating the efficiency is

$$\eta_d = \eta_0 (1 - 0.075R), \quad (2-3)$$

where η_0 is the efficiency from the wall plug to the diode (28%), and R is the chamber radius (m). The factor η_0 includes the efficiency of the power supplies (98%), Marx banks (83%), pulse-forming lines (93%), diode (45%), and focusing (90%). These nominal values are taken from a survey of current technology.¹⁷ The factor in parentheses in Eq. (2-3) represents the transport loss in the chamber, and is still somewhat speculative since high-power LIBs have not yet been channel-focused on a target.

3. TARGET-GAIN MODELS

Algorithms for target gain as a function of driver energy are based on laser curves available in 1985. These curves were presented to the National Academy of Sciences review in May 1985, and were subsequently used in LLNL economic studies.¹⁸ The HIB-gain curves are based on curves published by Lindl and Mark.¹⁹ An updated version of the HIB curves will be incorporated in the near future. SAFIRE does not contain curves specifically for an LIB driver, but the user can specify any of the available curves with any driver.

The algorithm used for the gain curves is

$$G = A + B \ln [(E_d + D)/C], \quad (3-1)$$

where E_d is the driver energy (MJ), and A, B, C, and D are fitting coefficients.

The fitting coefficients for the laser curves are given in Table 3-1. There are three possible curves, corresponding to advanced target concepts and to the upper and lower curves of the best estimates for current designs. The three curves are shown in Fig. 3-1.

The coefficients for single- and double-shell HIB targets are given in Table 3-2. The HIB curves are distinguished by the parameters $r^{3/2}R$, where r is the beam radius in centimeters, and R is the ion range in g/cm^2 . The single- and double-shell HIB-gain curves are shown in Figs. 3-2(a) and 3-2(b), respectively.

Table 3-1. Single-shell target-gain coefficients.

	A	B	C	D
Advanced	100	312	02.5	2.0
Current designs (upper curve)	30	127	2.7	2.0
Current designs (lower curve)	10	44	3.25	2.0

Figure 3-1. Target gain curves for advanced target concepts and for the best estimates for current designs using a laser driver.

Table 3-2. Coefficients for single- and double-shell HIB-targets.

	A	B	C	D
Single-shell parameters				
$r^{3/2}_R = 0.005$	20	91	1.1	0.0
$r^{3/2}_R = 0.01$	20	113	1.7	0.0
$r^{3/2}_R = 0.02$	20	157	3.0	0.0
$r^{3/2}_R = 0.04$	20	208	5.2	0.0
Double-shell parameters				
$r^{3/2}_R = 0.005$	75	121	3.1	0.0
$r^{3/2}_R = 0.01$	63	143	3.8	0.0
$r^{3/2}_R = 0.02$	50	178	4.9	0.0
$r^{3/2}_R = 0.04$	33	204	6.9	0.0

Figure 3-2. Target gain curves for (a) single-shell, and (b) double-shell targets using a heavy-ion-beam driver.

4. REACTOR-CHAMBER AND BREEDING-BLANKET MODELS

4.1 HYLIFE

HYLIFE-type⁶ chambers are scaled in a series of four steps.

Step 1. Scaling the First-Structural-Wall Radius and Wall Thickness

In theory the FSW radius could be treated as a free parameter, and all other chamber parameters adjusted to accommodate design constraints. However, this approach leads to unreasonable thicknesses and flow rates as parameters are varied from the design point. Hence, it is best to scale the FSW radius with a parameter such as target yield or fusion power. The scaling used here is

$$\left(\frac{R}{5}\right)^2 = \frac{Y}{1800} \quad (4-1)$$

$$\left(\frac{R}{5}\right)^2 = \frac{P}{2700} \quad (4-2)$$

where R is the FSW radius, Y is the target yield, P is the fusion power, and all are normalized to the point design. The user can choose to scale the radius with either yield or fusion power.

Equations similar to (4-1) and (4-2) are used to scale the chamber height. The equations are

$$\left(\frac{H}{8}\right)^2 = \frac{Y}{1800} \quad (4-3)$$

or

$$\left(\frac{H}{8}\right)^2 = \frac{P}{2700} \quad (4-4)$$

where H is the chamber height and both equations are normalized to the point design. The HYLIFE chamber is shown schematically in Fig. 4-1.

Having obtained the chamber dimensions, we can compute the effective thickness of the lithium jet array, t_{Li} , to satisfy constraints on atomic displacement and helium production in the first wall. For a ferritic-steel first wall with a 30-year lifetime at 70% plant capacity, these constraints are related to the jet array thickness by^{20,21}

Figure 4-1. The HYLIFE reaction chamber.

$$9.5 \frac{\text{DPA}}{\text{yr}} \geq 1.28 \frac{P}{R^2} \exp(-3.1 t_{Li}) \quad (4-5)$$

$$24 \frac{\text{appm He}}{\text{yr}} \geq 2.6 \frac{P}{R^2} \exp(-4.2 t_{Li}) , \quad (4-6)$$

where P is the fusion power in megawatts, and R and t_{Li} are in meters. The parameters on the left of the inequalities are consistent with the point designs. The maximum value of t_{Li} from Eqs. (4-5) and (4-6) is used for the effective lithium thickness.

Step 2. Lithium Injection Speed and Packing Fraction

The time required for the jets to traverse the length of the chamber must be no greater than the inverse of the pulse repetition rate. The lithium injection speed is computed from this, using equations derived from elementary mechanics. The lithium head on the upper side of the nozzle plate follows from Bernoulli's equation. The packing fraction over the length of the fall is then computed by assuming the packing fraction at the nozzle plate is 77%.

Step 3. First-Wall Temperature Rise and Thickness

The first wall is designed to satisfy an ASME-approved criterion for pressure vessel design²²:

$$\sigma_{im} \leq \frac{S_f(T)}{2} , \quad (4-7)$$

$$\sigma_{im} + \sigma_{th}(\Delta T) \leq S_y(T) , \quad (4-8)$$

where σ_{im} and σ_{th} are the impact and thermal stress, respectively, and S_f and S_y are the fatigue and yield strength, respectively. The dependence of the fatigue and yield strength on temperature, T, and the dependence of the thermal stress on the temperature difference across the FSW, ΔT , have been explicitly denoted.

When the stresses take on their limiting values, Eqs. (4-7) and (4-8) can be combined as

$$2\sigma_{th}(\Delta T) + S_f(T) = 2S_y(T). \quad (4-9)$$

For a wall with uniform internal heating (e.g., from neutrons) that is cooled on both sides, the thermal stress is related to the temperature difference by

$$\sigma_{th}(\Delta T) = \frac{2\alpha\Delta TE}{3(1-\nu)}, \quad (4-10)$$

where α is the thermal expansion coefficient, E is Young's modulus, and ν is Poisson's ratio. The temperature at the surfaces of the FSW is assumed to be the same as the lithium-coolant temperature of 500°C. Hence, the temperature at the center of the wall is 500°C + ΔT . Equations (4-9) and (4-10) can then be used to solve for ΔT .

The wall thickness t_w follows from Fourier's law,

$$q'' \Sigma = \frac{8k\Delta T}{t_w^2}, \quad (4-11)$$

where q'' is the neutron energy flux (MW/m^2), Σ is the heating kerma factor, and k is the thermal conductivity. The kerma factor used in the algorithm is 4.43 m^{-1} .

Step 4. Distance from the Chamber Center to the Jet Array

An analytic model is used to compute the impact stress as a function of the FSW radius, target yield, jet-array thickness, packing fraction, and jet array inner radius.²² All the parameters describing the chamber except the inner radius of the jet array are calculated by Steps 1 to 3. The model described in Ref. 22 can then be used to solve for the inner radius of the jet array.

4.2 HIBALL

A cross section of the HIBALL reactor is shown in Fig. 4-2 (Ref. 7). Although the design was developed for a heavy-ion driver, it is also suitable for use with a KrF-laser driver. The steps for scaling the cavity parameters are described below.

Figure 4-2. The HIRALL reaction chamber.

Step 1. Chamber Radius and PbLi Blanket Thickness

The chamber radius is computed by Eqs. (4-12) and (4-13) for the same reasons described in Step 1 of the HYLIFE scaling.

$$\left(\frac{R}{7}\right)^2 = \frac{Y}{400} \quad (4-12)$$

$$\left(\frac{R}{7}\right)^2 = \frac{P}{2000} \quad (4-13)$$

where R is the chamber radius (m), Y is the target yield (MJ), and P is the fusion power (MW).

The effective thickness of the PbLi curtain, t_{PbLi} , is also computed in a manner similar to that used in the HYLIFE algorithms. The scaling coefficients differ to reflect the change in neutronics. For an HT-9-steel first wall with a 30-year lifetime at 70% plant capacity, the curtain thickness scales with power and FSW radius as

$$3.84 \frac{\text{DPA}}{\text{yr}} \leq 1.31 \frac{P}{R^2} \exp(-4.0 t_{\text{PbLi}}) \quad (4-14)$$

$$0.52 \frac{\text{appm}}{\text{yr}} \leq 8.73 \frac{P}{R^2} \exp(-10.0 t_{\text{PbLi}}), \quad (4-15)$$

where P is in megawatts, and R and t_{PbLi} are in meters. The parameters on the left side of the inequalities are consistent with the HIBALL point design.

Step 2. First-Wall Temperature Rise and Thickness

There is little impact stress on the FSW. Therefore, the first-wall design criterion is

$$\sigma_{\text{th}}(\Delta T) \leq S_y(T). \quad (4-16)$$

The temperature rise in the first wall is computed using Eqs. (4-10) and (4-16). The first-wall thickness is then computed using Eq. (4-11). The neutron-heating kerma factor used in this calculation is 12.3 m^{-1} .

Step 3. Distance from the Chamber Center to the Tubes

The x-ray energy emitted by the target, Y_{xray} , is assumed to be absorbed in a thin layer of PbLi at the surface of the first tube banks. The thin layer is ablated toward the chamber centerline, imparting an impulse I on the tube bank that is given by

$$I = [2M_{\text{max}}(Y_{\text{xray}} - HM_{\text{max}})]^{1/2}/t_{\text{xray}}, \quad (4-17)$$

where M_{max} is the mass of ablated material, H is the heat of vaporization, and t_{xray} is the x-ray deposition time.

The evaporated mass is computed by assuming the layer is heated from the ambient temperature T_0 to the temperature T_r at which the layer will quickly radiate energy. The justification for this upper bound is that radiation is assumed to transport energy from the ablated gas to the tube surface and ablate additional PbLi until the gas can no longer radiate. From opacity data, T_r is around 1 eV. Expressed mathematically,

$$M_{\text{max}} = \frac{Y_{\text{xray}}}{H + \int_{T_0}^{T_r} c_p(T) dT}, \quad (4-18)$$

where c_p is the coolant heat capacity. The maximum areal impulse considered tolerable in the HIBALL design is about $50 \text{ N/m}^2 \cdot \text{s}$. The inner radius of the tube banks, R_i , is computed from this constraint and Eqs. (4-17) and (4-18).

Step 4. Number and Size of the SiC Tubes

The tube area throughout the chamber must be large enough to recondense the evaporated PbLi between shots. For a sticking coefficient of unity the rate at which evaporated mass condenses is given by the product of the vapor flux and tube area,

$$\frac{dM}{dt} = \left(\frac{2}{\pi} \frac{\bar{R}T}{m} \right)^{1/2} \frac{r_t n_t M}{R^2 - n_t r_t^2} \quad (4-19)$$

where $\bar{R}$ is the gas constant, m is the molecular mass, r_t is the tube radius, and n_t is the number of tubes. Solving Eq. (4-19) for the tube radius yields

$$r_t = \left(\frac{2}{\pi} \frac{\bar{R}T}{m} \right)^{1/2} \frac{\tau n_t r_t^2}{(R^2 - n_t r_t^2) \ln \left(\frac{M_{\max}}{M_{\min}} \right)} \quad (4-20)$$

where $M_{\min}$ is the mass corresponding to the gas density requirements for beam transmission (4×10^{10} atoms/cm³), and τ is the time between shots. The effective thickness is defined by

$$t_{\text{PbLi}} = \frac{n_t r_t^2}{R^2 - R_i^2} (R - R_i) \quad (4-21)$$

Equations (4-20) and (4-21) can be combined to solve for n_t and r_t .

4.3 EAGLE

A cross section of the EAGLE chamber is shown in Fig. 4-3 (Ref. 8). The HT-9 first wall is protected from target x rays and debris by a chamber gas. The energy deposited into the gas initiates a shock wave. The lithium spray in the cavity helps to attenuate the shock as it approaches the wall, thus reducing the impact stress. The design lifetime of the first wall is ten years.

The chamber radius is chosen to satisfy the constraints on neutron damage and fatigue stress. The constraint on neutron damage for a seven-year lifetime is related to the yield and wall radius by

$$\frac{fP \times 7 \text{ yrs}}{4\pi R^2} \leq 6 \text{ MW}\cdot\text{yr}/\text{m}^2 \quad (4-22)$$

where f is the neutron fraction of the fusion power P_f .

Figure 4-3. The EAGLE reaction chamber.

The constraint from impact stress is computed by assuming the response time of the wall is much greater than the time τ for wall reflection. The impact stress is then given by

$$\sigma_{im} = p\tau/t_w (E_w/\rho_w)^{1/2}, \quad (4-23)$$

where p is the pressure at the wall, t_w is the wall thickness, and E_w and ρ_w are the elastic modulus and density of the HT-9 first wall, respectively. The time for shock reflection is approximated as the time τ to traverse the effective thickness of the lithium spray, t_s ,

$$\tau = \frac{2t_s}{c}, \quad (4-24)$$

where c is the sound speed in liquid lithium. The effective thickness chosen is the one required for a 100°C temperature rise per pulse. The pressure p in Eq. (4-23) is given by

$$p = \rho_L u c, \quad (4-25)$$

where u is the shock speed. The shock speed is normalized to the results published in the EAGLE⁸ report by the relation

$$u \sim (Y/R)^{3/2}, \quad (4-26)$$

where the dependence on yield and position are taken from strong shock theory. Equations (4-23) and (4-26) can be combined to arrive at a relationship between target yield, wall thickness, impact stress, and wall radius of the form

$$Y \sim (t_w \sigma_{im})^{2/3} R^{7/3}. \quad (4-27)$$

The maximum value of R given by Eqs. (4-22) and (4-27) is the cavity radius.

4.4 CASCADE

The Cascade chamber concept is shown in Fig. 4-4 (Ref. 5). The blanket consists of 90 cm of LiAlO_2 breeder behind a 10-cm layer of beryllium oxide

Figure 4-4. The Cascade reaction chamber.

and a carbon surface layer. Chamber rotation forces the granular blanket against the cavity structure, which consists of SiC panels held in compression by Nicaloy composite tendons. The tendons are thermally isolated from the SiC panels, which are capable of operating at higher temperatures than Nicaloy. The nominal operating parameters for Cascade are 300 MJ of yield at 5 Hz in a 5-m cavity.

An attractive aspect of the Cascade cavity is that the dimensions are relatively insensitive to the target yield and repetition rate. If we assume the wall stresses are the only limiting factor, the cavity and blanket dimensions can remain fixed as yield and repetition rate are varied, because the Nicaloy tendons can be sized at will. As a result of the insensitivity, the nominal cavity dimensions are kept constant. The only function of the cavity scaling subroutine is to assign values to cavity parameters that are needed in other subroutines.

4.5 DRY-WALL CHAMBERS

A model for scaling dry-wall chambers protected by sacrificial liners has been incorporated into the SAFIRE code.⁹ The model predicts the minimum chamber radius given the fusion yield, pulse repetition rate, and desired first-wall lifetime. To predict the radius, the model considers two phenomena: sacrificial liner ablation caused by the temperature rise in each pulse, and steady-state neutron-irradiation damage. The steps are described below.

Step 1

The allowed liner loss per shot Δx (mm) is first computed as

$$\Delta x = x_s / (v L_w), \quad (4-28)$$

where x_s is the total sacrificial thickness (mm), v is the pulse repetition rate per cavity (Hz), and L_w is the desired first-wall lifetime (s). The liner loss per shot from ablation is directly related to the maximum surface temperature of the liner per shot. A rigorous solution for the loss rate requires a numerical hydrodynamics treatment, including a model for the

liner equations of state. For this algorithm, we use the data relating the derived liner loss per shot to the maximum surface temperature required to achieve such a loss, $T_{\max}$ ($^{\circ}\text{C}$) (Ref. 10).

Step 2

Next, the reactor cavity radius corresponding to the maximum acceptable surface temperature $T_{\max}$ is computed. This is done by first computing the temperature rise through the liner and wall, ΔT , given by

$$\Delta T = T_{\max} - T_0,$$

where T_0 is the peak first-wall coolant temperature. The temperature rise can be expressed as the sum of the steady-state temperature rise across the liner and wall due to the power deposited on the liner surface, and the effectively instantaneous temperature rise at the exposed liner surfaced from pulsed heating. Thus,

$$\Delta T = \frac{C_1 v Y (1 - f) (x_1/k_1 + x_2/k_2)}{R^2} + \frac{C_2 (1 - f) Y}{R^{2.5}} + \frac{C_1 C_3 v Y^2 (1 - f) (1/k_2)}{R^3}, \quad (4-29)$$

where

C_1 = constant used for unit conversion,

v = repetition rate (Hz),

Y = fusion yield (MJ),

f = neutron energy fraction,

x_1 = effective sacrificial-liner thickness at the start of life (mm),

x_2 = effective first-wall thickness before coolant (mm),

k_1 = thermal conductivity of the sacrificial liner (MW/mm $\cdot^{\circ}\text{C}$),

k_2 = thermal conductivity of the first wall (MW/mm $\cdot^{\circ}\text{C}$),

R = first-wall radius (m),

C_2 = empirical scaling constant derived from work presented in Ref. 4-10 ($^{\circ}\text{C}\cdot\text{m}^{2.5}/\text{MJ}$),

C_3 = empirical scaling constant.

The first term represents the steady-state temperature rise and the second term represents the instantaneous temperature rise at the liner surface.

The temperature drop at the interface between the first wall and the liner is not included. The assumption that x_1 is given by the start-of-life value rather than an effective value is conservative. We use Newton's method to invert the expression for ΔT and solve for R .

The radius required to limit radiation damage is computed from

$$D \geq \frac{L_w \nu Y f}{(3.16 \times 10^7) (4\pi R^2)} \quad (4-30)$$

where $D(\text{MW}\cdot\text{yr}/\text{m}^2)$ represents an integrated neutron fluence limit for neutron damage. The lumped parameter D is calibrated from neutronic design results. The radial blanket structure, the axial blanket structure, and the first wall are each allowed a unique fluence limit and desired life, so three minimum cavity radii are calculated. Given the ablation radius, the three neutron damage radii, and an externally supplied minimum cavity radius, the chamber-scaling routine selects the largest of these. Because only one of the criteria is satisfied exactly, the routine performs the above calculations in the inverse mode to determine the expected first-wall and blanket structure lifetimes for selected final first-wall radius.

The routine allows either a spherical or a right circular cylindrical chamber shape. Also, the present version has a data base applicable to three wall types: a graphite sacrificial liner over a stainless steel wall, a niobium liner over a steel wall, and an entirely steel wall. Because the required thickness of the wall to withstand the microexplosion impact stress is a function of the yield and radius, an optional scaling relation is provided:

$$x_2 = C_4 (Y/R^2) R = C_4 Y/R \quad (4-31)$$

where C_4 is a normalization coefficient. The above equation is a simple analogy to the design of pressure vessels for static load. Finally, an option is provided that allows some fraction of the ablated wall materials to beneficially recondense on the sacrificial liner is provided. This has the effect of increasing T_{max} and decreasing the ablation radius for the same effective liner loss per shot.

4.6 TRITIUM INVENTORY

The deuterium and tritium burned, as well as the helium generated per shot, are both given by

$$m = 5.9 \times 10^{-7} AY, \quad (4-32)$$

where m is the mass change per shot (g), A is the isotopic mass of interest (amu), and Y is the target yield (MJ). For the three isotopes of interest, $A = 2, 3$, and 4 . Multiplying Eq. (4-32) by the repetition rate gives the rate of fuel burn and helium generation. The fuel injection per shot is obtained by dividing Eq. (4-32) by the burn factor F . This parameter could affect target-factory costing, and is useful in assessing the tritium inventory.

For chamber designs utilizing a liquid-metal liner inside the first wall, the fractions of fuel trapped in the liquid metal are specified by input or by default. The untrapped portions are assumed to be vacuum pumped from the chamber. A global mass balance is accomplished by multiplying Eq. (4-32) by the total number of chambers making up a unit.

5. BALANCE-OF-PLANT MODELS

The BOP is concerned primarily with the power-cycle conversion systems. The algorithms for the BOP are basically divided into two categories, the Rankine steam cycle and the Brayton gas cycle. Figures 5-1 and 5-2 illustrate the power cycle schematic flow diagrams.

5.1 MULTIPLE SYSTEMS

Having scaled each of the plant subsystems, we next account for the number of subsystems associated with a single BOP. In particular, this section accounts for multiple chambers, multiple target factories, and multiple drivers associated with a single BOP. The case of a single driver and target factory associated with several complete power units (i.e., chambers and BOPs) is discussed in Section 8.4.

The number of multiple chambers affects both direct cost and the amount of electricity produced. Having multiple chambers relieves performance requirements of the chamber design, but typically results in increased cost and recirculating power. Cost is therefore strongly dependent on the chamber concept. Additional HYLIFE chambers, for example, would also require a large investment in added pumps and piping.

The number of target factories affects only direct cost since the target factories do not enter into the power cycle. The details of this effect can be understood by examining the target-factory costing model in Section 7.9.

Having multiple drivers affects both the direct cost and recirculating power in a manner that depends on the sensitivity of cost and efficiency to repetition rate. The cost algorithms described in Section 7.8 are independent of repetition rate, indicating an economic incentive to have only one driver. A single driver also tends to maximize the use of driver power supplies, hence maximizing the efficiency. The economic penalties of multiple drivers can be severe because the driver cost is a significant fraction of the total cost.

The total power per plant is the product of power per chamber and the number of chambers. Similar calculations are made to total the tritium production rate and inventory.

Figure 5-1. Heat-transfer and power-generation components of a liquid-metal-cooled reactor using a steam cycle.

Figure 5-2. Heat-transfer and power-generation components of a helium-cooled reactor using a closed Brayton cycle with regeneration.

5.2 TRITIUM EXTRACTION

This subroutine calculates the total lithium flow rate through a molten-salt extraction system required to keep the plant tritium inventory at a prescribed level. It also calculates the electric power required to do the processing. The molten-salt extraction process is described in Refs. 23 and 24, and the model used here is also discussed in Ref. 9.

The lithium flow rate through the recovery system is given by

$$\dot{m}_L = \dot{m}_g I_L / \eta_e I_{ss} \quad (5-1)$$

where

$\dot{m}_g$ = total tritium generation rate in lithium (g/s),

I_L = total lithium inventory (g),

η_e = the effective removal efficiency,

I_{ss} = the steady-state tritium inventory (g).

The total lithium inventory I_L is calculated from the results of the BLNKT subroutine. The tritium generation rate $\dot{m}_g$ is calculated in the TRITFL subroutine. For concepts such as HYLIFE and EAGLE, the generation rate includes both the tritium that is bred in the lithium, and the unburned tritium from the target that is deposited directly in the lithium.

The effective removal efficiency is calculated from

$$\eta_e = c D_v \eta / (c D_v \eta + 1) \quad (5-2)$$

where

c = efficiency of tritium recovery from the salt (0.9),

D_v = volumetric distribution coefficient of tritium between the lithium and the salt (2.0),

η = efficiency factor that accounts for nonequilibrium tritium distribution during contacting (0.3).

Using the default values that are indicated in parentheses gives an effective recovery efficiency η_e of 0.35.

The steady-state tritium inventory (I_{ss}) is either input directly by the user, or is calculated from the total lithium inventory using the steady-state concentration, which is input by the user.

The number of extractor units is given by

$$N_e = \frac{(\dot{m}_L / \rho_L)}{3200} \quad (5-3)$$

where ρ_L is the lithium density (g/cm^3). The value of N_e is rounded up to the nearest integer. The calculation of the number of extraction units is based on a capacity per extractor of $6400 \text{ cm}^3/\text{s}$ (lithium plus salt) in a process where equal volumes of salt and lithium are contacted. The power requirements for tritium extraction is 3.73 KW_e per extractor unit. The capital cost of the tritium extraction system is taken to be proportional to the number of extractor units.

5.3 GROSS THERMAL POWER

The total thermal power generated in a reactor (including the effects of neutron energy multiplication) is the power input to the power conversion cycle,

$$P_t = N_c (P_B + P_w), \quad (5-4)$$

where N_c is the number of reactor chambers, and P_B and P_w are the blanket and first-wall thermal powers. The BOP main subroutine receives the thermal power as output from the reactor performance routines and sends it on to compute the gross electric power, based on the power cycle efficiency.

5.4 TURBINE CYCLE EFFICIENCY

The steam cycle efficiency is based on algorithms presented in Ref. 25. It is calculated as follows:

$$\eta = 1.0/\text{HR}, \quad (5-5)$$

where HR is the heat rate in J/J as given below as a piecewise linear fit of data.

$$\begin{aligned}
HR &= 3.209 - (T_S - 200) \times 7.882 \times 10^{-4} - CF_p && \text{for } 200 \leq T_S < 420^\circ\text{C} \\
&= 3.035 - (T_S - 420) \times 1.582 \times 10^{-3} - CF_p && \text{for } 420 \leq T_S < 480^\circ\text{C} \\
&= 2.940 - (T_S - 480) \times 1.319 \times 10^{-3} - CF_p && \text{for } 480 \leq T_S < 510^\circ\text{C} \\
&= 2.901 - (T_S - 510) \times 1.108 \times 10^{-3} - CF_p && \text{for } 510 \leq T_S < 540^\circ\text{C} \\
&= 2.868 - (T_S - 540) \times 1.105 \times 10^{-3} - CF_p && \text{for } 540 \leq T_S < 565^\circ\text{C}
\end{aligned}$$

where CF_p = correction factor for pressure, and T_S = steam temperature ($^\circ\text{C}$):

$$\begin{aligned}
CF_p &= (p_S - 1.5) \times 5.274 \times 10^{-2} && \text{for } 1.5 \leq p_S < 6 \text{ MPa} \\
&= 2.373 \times 10^{-1} + (p_S - 6) \times 4.249 \times 10^{-2} && \text{for } 6 \leq p_S < 9 \text{ MPa} \\
&= 3.648 \times 10^{-1} + (p_S - 9) \times 2.124 \times 10^{-2} && \text{for } 9 \leq p_S < 12.5 \text{ MPa} \\
&= 4.392 \times 10^{-1} + (p_S - 12.5) \times 1.062 \times 10^{-2} && \text{for } 12.5 \leq p_S < 17 \text{ MPa}
\end{aligned}$$

where p_S = steam pressure (MPa).

The Brayton gas-turbine cycle efficiency is calculated based on the thermodynamics of the cycle assuming that the helium behaves as a perfect gas. This assumption allows one to generate an explicit equation for the efficiency based on operating points of the cycle and its components²⁶:

$$\eta_t = \frac{\eta_e T_p \left\{ 1 - \frac{1}{[R_p(1 - \delta)]^\alpha} \right\} - \frac{3T_m [R_p^{(\alpha/3)} - 1]}{\eta_c}}{T_p - T_m(1 - \eta_r) \left\{ 1 + \frac{3 [R_p^{(\alpha/3)} - 1]}{\eta_c} \right\} - T_p \eta_r \left\{ 1 - \eta_e \left\{ 1 - \frac{1}{[R_p(1 - \delta)]^\alpha} \right\} \right\}}$$

(5-6)

where

- η_t = cycle conversion efficiency,
- η_e = turbine efficiency,
- η_r = regenerator efficiency,
- R_p = overall pressure ratio,
- δ = fractional pressure loss,
- $\alpha = (\gamma - 1)/\gamma$, where γ is specific heat ratio,

T_m = cycle minimum temperature,
 T_p = cycle maximum temperature,
 η_c = compressor efficiency.

5.5 GROSS ELECTRIC POWER

Assuming an isentropic turbine/generator, the gross electric power is given by

$$P_g = \eta_t P_t, \quad (5-7)$$

where η_t is the turbine cycle efficiency, and P_t is the gross thermal power. The power rejected to the condensation systems is then $(1 - \eta_t)P_t$.

5.6 STEAM TEMPERATURE

The exit temperature of steam as it leaves the steam generator is calculated simply as the difference of two numbers--the coolant hot leg temperature, which is an input, and the temperature difference between the coolant hot leg and the steam, which is assumed to be 20°C:

$$T_s = T_h - 20. \quad (5-8)$$

5.7 STEAM PRESSURE

The pressure of the steam, whether saturated or superheated, is obtained from a fit to standard steam-table data. Figure 5-3 shows the curve fit, which is excellent and indistinguishable from the steam-table data. For superheated steam, one must calculate a steam-saturation temperature to use the equation. This saturation temperature is given by

$$T_{sat} = T_s - \Delta T_{pc}, \quad (5-9)$$

Figure 5-3. Pressure-temperature saturation line for water.

where T_s ($^{\circ}\text{C}$) is the actual steam temperature and ΔT_{pc} is the primary-coolant heat-exchanger temperature difference. The pressure in MPa is

$$p_s = 2.683 \times 10^{-10} (T_{sat})^{4.24127} . \quad (5-10)$$

For a saturated steam cycle, the steam temperature $T_s = T_{sat}$ is used in the equation.

5.8 STEAM FLOW RATE

The steam flow rate is based on an energy balance across the steam generator:

$$P_t = \dot{m}_s c_p \Delta T = \dot{m}_s \Delta h \quad (5-11)$$

where P_t is the total thermal power carried away at a mass flow rate $\dot{m}_s$ and a change in enthalpy Δh . Solving for $\dot{m}_s$ gives

$$\dot{m}_s = \frac{P_t}{\Delta h} . \quad (5-12)$$

The enthalpy change Δh is the difference between enthalpies, where h_{st} is the enthalpy at the steam generator outlet and h_{fw} is the enthalpy of the feedwater at the steam generator inlet, respectively (states 1' and 4 in Fig. 5-4). Using a subroutine that interpolates steam-table enthalpy data as a function of temperature and pressure as calculated above in Eqs. (5-9) and (5-10), we obtain the steam flow rate

$$\dot{m}_s = \frac{P_t}{h_{st} - h_{fw}} . \quad (5-13)$$

Figure 5-4. Rankine cycle with superheat.

5.9 PRIMARY COOLANT FLOW RATE

The flow rate of coolant follows the same principle as that described in Section 5.8 above:

$$\dot{m}_{pc} = \frac{P_t}{C_p \Delta T_{pc}} , \quad (5-14)$$

where C_p is the coolant heat capacity and ΔT_{pc} is the primary coolant temperature difference across the heat exchanger.

5.10 SECONDARY COOLANT FLOW RATE

If one assumes that the temperature difference across a heat exchanger is the same for both streams, then the secondary coolant flow rate is similar in form to that described for the primary coolant:

$$\dot{m}_{sc} = \frac{P_t}{C_p \Delta T_{sc}} , \quad (5-15)$$

where C_p , the heat capacity, is not necessarily the same as that used in Eq. (5-14) because the primary and secondary coolants could be different.

5.11 PUMPING POWER

The pumping power is that power needed to move a fluid around a closed path where frictional losses cause a decrease in pressure, Δp . The total power consumed is

$$P_p = N_c \left[A_1 (\dot{m}_{pc}/N_c)^{2.8} + A_2 (\dot{m}_{sc}/N_c)^{2.8} \right] , \quad (5-16)$$

where A_1 and A_2 are coolant-dependent constants, $\dot{m}_{pc}$ and $\dot{m}_{sc}$ are the coolant flow rates, and N_c is the number of reactor chambers. The 2.8 exponent is derived below.

The standard pumping power equation is

$$P_p = \frac{\dot{m} \Delta p}{\rho} , \quad (5-17)$$

where ρ is the fluid density, $\dot{m}$ is the mass flow rate and Δp is the frictional pressure loss. The frictional pressure loss is

$$\Delta p = \rho f \frac{L}{D} \frac{V^2}{2}, \quad (5-18)$$

where V is the velocity, f is the friction factor, and L/D is the coolant line-length-to-diameter ratio. Using the Blasius friction factor for turbulent pipe flow, we have

$$f = \frac{0.316}{(VD/\nu)^{0.25}}, \quad (5-19)$$

where ν is the fluid kinematic viscosity. Substituting f and $\dot{m} = \rho AV$ (where A is the pipe area) gives

$$P \sim \dot{m}^{2.75}, \quad (5-20)$$

which when rounded gives

$$P \sim \dot{m}^{2.8}, \quad (5-21)$$

or the shift to 2.8 from 2.75 can be viewed as the increase in power due to pump inefficiencies.

6. EXTERNAL BREEDING BLANKETS

The SAFIRE code can accommodate up to six radial and axial blanket regions exterior to the FSW. Algorithms accounting for tritium breeding and power multiplication are applied to each of the blanket regions. The input required to utilize the algorithms consists of the blanket thickness, material types and volume fractions, and tritium breeding ratio. For generic reactor concepts, such as the dry-wall concept, the input values of breeding and energy multiplication factors are for 100% solid-angle fraction, and the algorithms generate a solid-angle correction factor. For scaling the HYLIFE,⁶ HIBALL,⁷ or EAGLE⁸ point designs, the breeding and energy multiplication factors given in those studies already include a solid-angle correction factor and are to be used as the input.

The volume of each material is calculated from the input value of blanket thickness and material volume fractions, along with the cavity radius from previous calculations. The tritium production rates then follow as

$$R_p = 0.056 B \alpha P_f, \quad (6-1)$$

where

- R_p = production rate (kg/yr),
- B = breeding ratio per source neutron,
- α = plant capacity factor,
- P_f = fusion power (MW).

The thermal power is greater than the fusion power because of energy multiplication from neutron reactions in the blanket:

$$P_t = P_f \sum_i C_i N_i, \quad (6-2)$$

where

- P_t = thermal power (MW),
- C_i = reaction-dependent conversion factor for reaction type i ,
- N_i = number of reactions per source neutron for type i .

The conversion factor is an input parameter for tritium breeding blankets. The total thermal power from exothermic reactions is obtained by summing over the materials in each blanket and then over the number of blankets. The blanket coolant is one of the materials in each blanket. The flow rate is calculated from simple thermal hydraulic considerations.

PART B. COST SCALING

7. DIRECT COSTS

The SAFIRE code calculates direct costs of the HYLIFE,⁶ HIBALL,⁷ EAGLE,⁸ and dry-wall reactor concepts at the three-digit account level. Direct costs of the Cascade⁵ reactor are calculated at the two-digit level. This difference in costing derives more from the history of the SAFIRE code's development than from fundamental differences between the reactor concepts. The concepts for the HYLIFE, HIBALL, EAGLE, and dry-wall reactors utilize a steam cycle with liquid-metal primary coolants, whereas the Cascade concept utilizes a modified Brayton cycle. In all cases, the direct costs are calculated for a reference year that is a function of when the costing was done. Each cost account is then adjusted to a common year using inflation factors.

Cost accounts for cavity-related items are generally scaled from the respective point design studies, whereas costs for facility and BOP accounts are benchmarked to the Energy Economic Data Base for fission reactors.^{1,2} It is assumed that the recommendations described there for reducing construction times and supervision costs in the 1990s have been implemented.

7.1 LAND AND LAND RIGHTS (ACCOUNT 20)

Account 20 = 5.0 M\$. (7-1)

7.2 STRUCTURES AND IMPROVEMENTS (ACCOUNT 21)

For the Cascade reactor, the total cost of structures and improvements (Account 21) is given by

$$C_{SAI} = 84.3(P_t/1670)^{0.20} \quad (\text{M\$}) . \quad (7-2)$$

where P_t is the thermal power in MW_t . The numerical coefficients in Eq. (7-2) represent the point design values of cost (in 1985 dollars) and gross thermal power.

For the other reactor concepts, the structures and improvements account is divided into several subaccounts as indicated below.

7.2.1 Site Improvements and Facilities (Account 21.01)

$$C_{S1} = 28.8 \left(\frac{A_{BLOG}}{25,000} \right) \quad (\text{M\$}), \quad (7-3)$$

where A_{BLOG} is the total building projected area in m^2 summed from the following algorithms.

7.2.2 Reactor Containment Building (Account 21.02)

The cost of the reactor containment building (RCB) is given with and without an intermediate coolant loop. In general, building costs are proportional to the volume of the building, V , raised to some power less than unity. The volume is the product of the building area, A , and the building height, H .

a. With an Intermediate Coolant Loop:

$$C_{RCB} = 113.3 \left(\frac{V_{RCB}}{159,200} \right)^{0.7} \quad (\text{M\$}) \quad (7-4)$$

V_{RCB} = Volume of Reactor Containment Building (m^3)

$$= A_{RCB} \times H_{RCB}$$

$$A_{RCB} = N_c \left[900 \left(\frac{R + 10}{15} \right)^2 + 1800 \left(\frac{P_c}{3800} \right) \right] \quad (m^2)$$

$$H_{RCB} = 59 \text{ m},$$

where N_c is the number of reactor chambers, R is the chamber radius (m), and P_c is thermal power per chamber (MW).

b. Without an Intermediate Coolant Loop:

$$C_{RCB} = 73.4 \left(\frac{V_{RCB}}{85,668} \right)^{0.7} \quad (M\$) \quad (7-5)$$

$$A_{RCB} = N_c \left[484 \left(\frac{R+6}{11} \right)^2 + 968 \left(\frac{P_c}{3412} \right) \right] \quad (m^2)$$

$$H_{RCB} = 55 \text{ m ,}$$

where N_c , R , and P_c are as defined above. Constants are from the Energy Economic Data Base point designs.¹

7.2.3 Turbine Generator Building (Account 21.03)

$$C_{TGB} = 20.4 \left(\frac{V_{TGB}}{117,600} \right)^{0.85} \quad (M\$) \quad (7-6)$$

$$V_{TGB} = \text{Volume of Turbine Generator Building, } m^3$$

$$A_{TGB} = 2800 \left(\frac{P_{TG}}{1547} \right)^{0.3} (N_{TG})^{0.8} \quad (m^2)$$

$$H_{TGB} = 40 \text{ m ,}$$

where P_{TG} is the gross electric power of each of N_{TG} turbine generator units.

7.2.4 Cooling System Structure (Account 21.04)

$$C_{CSS} = 4.9 N_{TG} \left[\frac{P_{TG} (1 - \eta)/\eta}{2253} \right]^{0.3} \quad (M\$) , \quad (7-7)$$

where P_{TG} is the MW_e power of each of N_{TG} turbine generator units, and η is the turbine cycle efficiency as calculated in Part A, Section 5.4.

7.2.5 Other Plant Buildings (Account 21.06)

a. Radioactive Reactor Auxiliary Building:

$$C_{RABR} = 20.0 \left(\frac{V_{RABR}}{69,000} \right)^{0.8} \quad (\text{M\$}) \quad (7-8)$$

V_{RABR} = Volume of Radioactive Auxiliary Buildings (m^3)

$$A_{RABR} = 2300 \left(\frac{P_t}{3800} \right)^{0.1} \quad (\text{m}^2)$$

$$H_{RABR} = 30.0 \text{ m} ,$$

where P_t is the total thermal power in MW_t .

b. Non-Radioactive Reactor Auxiliary Building:

$$C_{RABNR} = 2.5 \left(\frac{V_{RABNR}}{5700} \right)^{0.85} \quad (\text{M\$}) \quad (7-9)$$

V_{RABNR} = Volume of Non-Radioactive Auxiliary Building (m^3)

$$A_{RABNR} = 190 \left(\frac{P_t}{3800} \right)^{0.1} \quad (\text{m}^2)$$

$$H_{RABNR} = 30 \text{ m} ,$$

where P_t is the total thermal power in MW_t .

c. Reactor Service Building:

$$C_{RSB} = 22.3 \left(\frac{V_{RSB}}{85,500} \right)^{0.8} \quad (\text{M\$}) \quad (7-10)$$

V_{RSB} = Volume of Reactor Service Building (m^3)

$$A_{RSB} = 1900 \left(\frac{P_t}{3800} \right)^{0.1} \quad (\text{m}^2)$$

$$H_{RSB} = 45 \text{ m} ,$$

where P_t is the total thermal power in MW_t .

d. Steam Generator Building:

$$C_{SG} = 17.4 \left(\frac{V_{SG}}{82,800} \right)^{0.8} \quad (\text{M\$}) \quad (7-11)$$

V_{SG} = Volume of Steam Generation Building (m^3)

$$A_{SG} = 1800 \left(\frac{P_{SG}}{475} \right)^{0.36} \frac{N_{SG}}{8} \quad (\text{m}^2)$$

$$H_{SG} = 46 \left(\frac{P_{SG}}{475} \right)^{0.1} \quad (\text{m}) .$$

where P_{SG} is the MW power per steam generator and N_{SG} is their number.

For the option of a single cooling loop, this cost is zero because the steam generators are now housed inside the reactor containment building.

e. Control Building:

$$C_{CB} = 19.0 \left(\frac{V_{CB}}{56,600} \right)^{0.85} \quad (\text{M\$}) \quad (7-12)$$

V_{CB} = Volume of Control Building (m^3)

$$A_{CB} = 1400 \left(\frac{P_t}{3800} \right)^{0.05} (N_{TG})^{0.1} (N_C)^{0.1} \quad (\text{m}^2)$$

$$H_{CB} = 40 \text{ m}$$

where P_t is the total thermal power in MW_t, N_{TG} is the number of turbine generators, and N_C is the number of reactor chambers.

f. Miscellaneous Structures:

$$C_{ms} = 16.3 \quad (\text{M\$}) . \quad (7-13)$$

This cost is taken from the Energy Economic Data Base 1990's LMFBR balance-of-building costs not accounted for above.^{1,2}

g. Tunnels:

$$C_{TUN} = 2.50 \times 10^{-3} V_{TUN} \quad (\text{M\$}) \quad (7-14)$$

$$V_{TUN} = \text{Tunnel Volume} \quad (\text{m}^3)$$

$$= \pi R_B^2 (L_B - W_{RCB}) N_B,$$

where R_B is the beam radius, L_B the length, W_{RCB} is the width of the reactor containment building, and N_B is the number of beams.

7.3 REACTOR PLANT EQUIPMENT (ACCOUNT 22)

For the Cascade reactor, this account scales as

$$C_{RPE} = 282.8 (P_t / 1670)^{0.36} \quad (\text{M\$}) \quad (7-15)$$

where P_t is the total thermal power in MW_t. The numerical coefficients in Eq. (7-15) represent the point-design values of cost in 1985 dollars and total thermal power.

For the HYLIFE, HIBALL, EAGLE, and dry-wall reactor concepts the reactor plant equipment is subdivided into the following accounts:

<u>Account</u>	<u>Item</u>
22.1	Cavity First Wall
22.2	External Blankets
22.3	Cavity Vacuum System
22.4	Target Delivery, Tracking, and Alignment
22.5	Tritium Extraction
22.6	Reactor Shielding
22.7	Primary Heat Transport

Because of the diversity of reactor concepts and the immature nature of technologies involved, the order of these accounts is not standardized. The algorithms used are described in the following subsections.

7.3.1 Cavity First Wall (Account 22.1)

The cavity first wall is costed assuming a cylindrical geometry consisting of two axial and one radial boundaries. The coordinates and thickness of each boundary are calculated by the cavity scaling algorithms described in Part A. The costing is given by

$$C_{FW} = [2\pi r^2 + 2\pi rh] \rho t c \times 10^{-6} \quad (\text{M\$}) , \quad (7-16)$$

where

- h and r = height and radius (m),
- ρ = material density (kg/m^3),
- t = thickness (m),
- c = unit cost ($\text{\$/kg}$).

The density and unit cost are input by the user or assigned default values, and correspond to as-fabricated-and-installed rather than raw material.

The first wall of the dry-wall and EAGLE reactor concepts is the first structure before an external blanket. The first wall of the HYLIFE and HIBALL reactor is the FSW enclosing the liquid-metal blanket.

7.3.2 External Blankets (Account 22.2)

External blankets and reflectors are segmented into radial and axial zones. Up to six zones can be defined, with each zone containing up to six different materials. The volume fraction and unit cost of each material are input by the user, as is the thickness of each zone. The volume of each zone is then calculated from the calculated cavity height and radius. The total cost of external blankets is given by

$$C_{EB} = 10^{-6} \sum_{i=1}^6 V_i \sum_{j=1}^6 F_{ij} C_{ij} \quad (\text{M\$}) , \quad (7-17)$$

where V_i is the volume of zone i (m^3), F_{ij} is the volume fraction of material j in zone i , and C_{ij} is the unit cost of material j in zone i ($\text{\$/m}^3$). For the dry-wall and EAGLE designs the external blankets are the

primary source of tritium breeding. The external blankets of the HYLIFE and HIBALL reactors serve mainly to cool the first wall and to reflect neutrons.

7.3.3 Cavity Vacuum System (Account 22.3)

Although all of the cavity designs encompassed by the SAFIRE code employ some type of cavity vacuum pumping, these components are not separately costed in the current version. These components typically cost on the order of tens of millions of dollars. This omission will be remedied in future versions of the code.

7.3.4 Target Delivery, Tracking, and Alignment (Account 22.4)

Although the technology for target tracking and alignment currently exists, the attention paid to this subsystem is insufficient for accurate cost scaling. At present this subsystem is assumed to cost \$20 million in 1980 dollars. This cost includes target delivery components, which are based on an unrelated technology and should eventually be costed separately.

7.3.5 Tritium Extraction (Account 22.5)

Although concepts exist for extracting tritium from the liquid metals of interest, and some of these concepts have been costed during the course of point-design studies, algorithms for extraction costs have not yet been implemented in the SAFIRE code. In lieu of an algorithm, the tritium extraction system is assumed to cost \$1 million in 1980 dollars. This cost includes any components for handling radioactive materials. When more detailed cost estimates become available, the handling components should be separately assessed.

7.3.6 Reactor Shielding (Account 22.6)

All cavities are assumed to be surrounded by a neutron shield consisting of borated, steel-reinforced concrete. A shield thickness t of 3.5 m is assumed in the radial and axial dimensions. The outer radius of the radial blanket R and the axial blanket height H are used in the costing calculation (Account 22.6) as follows:

$$C_{RS} = C_S \pi [2Rt(R + H) + t^2(4R + H + 2t)] 10^{-6} \quad (\text{M\$}) , \quad (7-18)$$

where C_S is the shielding cost coefficient ($\$/\text{m}^3$), and the radius, height and thickness are in meters. The value usually chosen for the unit cost coefficient is $\$15/\text{m}^3$ in 1980 dollars.

7.3.7 Heat Transport System (Account 22.7)

The algorithms used to calculate the heat transport system costs are given in this section. The constants used in the following equations are listed in Table 7-1.

a. HYLIFE Recirculating Jet Array:

$$C_{JA} = 28.3 [(F_t/10.2)^{0.5} - 1] + 21.0 [(F_t/10.2)^{0.74} - 1] \quad (\text{M\$}) , \quad (7-19)$$

where F_t is the total lithium flow rate (m^3/s) through the HYLIFE chamber. For low-power cases this quantity may be negative, and will then be reset to zero.

b. Intermediate Heat Exchanger:

$$C_{iHX} = AP_t \quad (\text{M\$}) , \quad (7-20)$$

where A is a coolant-dependent constant shown in the coefficient matrix at the end of this section, and P_t is the total thermal power. C_{iHX} is zero for the single cooling loop option.

c. Primary Loop Piping:

$$C_{PLP} = B \sqrt{P_t/\Delta T} \quad (\text{M\$}) , \quad (7-21)$$

where P_t is the total thermal power in MW_t and ΔT is the primary-coolant heat-exchanger temperature difference. The form is slightly different for PbLi.

Table 7-1. Coefficient matrix for Account 22.7.

Coolant	Constant											
	A	B	C	D	E	F	G	H	I	J	K	L
Li	0.0117	6.20	5.2×10^{-3}	9.0	2.22	3.3	46.4	7.7×10^{-3}	P_t	3800	3.11	0.074
Na	0.025	2.30	3.7×10^{-3}	20.0	1.27	0.24	21.6	3.6×10^{-3}	P_{EL}	500	1.46	0.074
PbLi	0.025	84.2	5.2×10^{-3}	9.0	1.806	3.3	46.4	7.7×10^{-3}	P_t	3800	3.11	0.074

d. Primary Coolant Cleanup Plant:

$$C_{PCCP} = C [V_{CB} + D (P_t/\Delta T)^{1.5}] \quad (M\$), \quad (7-22)$$

where C and D are coolant-dependent constants, V_{CB} is the volume of coolant in the blanket, P_t is the total thermal power, ΔT is the coolant heat-exchanger temperature difference, and $(P_t/\Delta T)$ is proportional to the coolant mass flow rate.

e. Primary Coolant Pumps and Motors:

$$C_{PCPM} = E (P_t/\Delta T)^{0.74} \quad (M\$), \quad (7-23)$$

where E is a coolant-dependent constant, P_t is the total thermal power, ΔT is the coolant heat-exchanger temperature difference, and $(P_t/\Delta T)$ is proportional to the coolant mass flow rate. The form is slightly different for PbLi.

f. Secondary Loop Piping:

$$C_{SLP} = F \sqrt{P_t/\Delta T} \quad (M\$), \quad (7-24)$$

where F is a coolant-dependent constant and P_t is the total thermal power. For the single cooling loop, F is set to zero.

g. Steam Generator:

$$C_{SG} = (G + HT_s)(I/J)^{0.89} \quad (M\$), \quad (7-25)$$

where G and H are coolant-dependent constants, T_s is the steam temperature, I is the thermal power for Li and PbLi and electric power for other coolants, and J is the steam-generator thermal capacity or turbine-generator electric capacity.

h. Secondary Coolant Pumps and Motors:

$$C_{SCPM} = K (P_t/\Delta T)^{0.74} \quad (M\$), \quad (7-26)$$

where K is a coolant-dependent constant, P_t is the total thermal power, ΔT is the coolant heat-exchanger temperature difference, and $(P_t/\Delta T)$ is proportional to the coolant mass flow rate.

i. Secondary Coolant Cleanup Plant:

$$C_{SCCP} = L (P_t/\Delta T)^{1.5} \quad (\text{M\$}) , \quad (7-27)$$

where L is a coolant-dependent constant, P_t is the total thermal power, ΔT is the coolant heat-exchanger temperature difference, and $(P_t/\Delta T)$ is proportional to the coolant mass flow rate.

j. Steam Separator:

$$C_{SS} = 11.4 \left(\frac{P_t}{3800} \right) \quad (\text{M\$}) , \quad (7-28)$$

where P_t is the total thermal power in MW_t .

k. Water Loop Piping:

$$C_{WLP} = 0.144 \sqrt{(P_t/3800)} \quad (\text{M\$}) , \quad (7-29)$$

where P_t is the total thermal power in MW_t .

l. Steam Superheater:

$$C_{SS} = (36.5 + 6.0 \times 10^{-3} T_s) (P_t/3800)^{0.89} \quad (\text{M\$}) , \quad (7-30)$$

where T_s is the steam temperature and P_t is the total thermal power in MW_t .

7.4 TURBINE PLANT EQUIPMENT (ACCOUNT 23)

For the Cascade reactor, the turbine plant equipment cost scales as

$$C_{TPE} = 183.7 (P_t/1670)^{0.85} \quad (\text{M\$}) , \quad (7-31)$$

where P_t is the total thermal power in MT_t (Ref. 5).

For the other reactor concepts, Account 23 is divided into subaccounts and the costs are calculated as described below.

The turbine plant equipment includes the steam handling, power conversion, and condensate/feedwater machinery of the steam cycle. All turbine plant equipment is designed to support turbine operation at the valves' wide-open, 5%-over-pressure point. The seven subaccounts of Account 23 are described as follows. The account breakdown follows that given in Ref. 1. The basic cost algorithm is

$$C = C_0 \left(\frac{P}{P_0} \right)^\alpha ,$$

where C_0 is the reference cost, taken from the Energy Economic Data Base 1990's LMFBR costs,² P and P_0 are scaling and reference parameters taken from Ref. 2, and α is a scaling exponent taken from Ref. 3 or Ref. 27.

Account 23.01: Turbine-Generator (turbomachinery, generator, exciter, stator cooling water system, gas systems, hydrogen-seal oil system, electro-hydraulic control system, turbine gland steam sealing system, moisture separator/reheater, drain system, lubricating-oil system, and turbine-oil conditioning system).

$$C_{TG} = 133.46 \left(\frac{P_{TG}}{1547} \right)^{0.7} N_{TG} \quad (\text{M\$}) , \quad (7-32)$$

where P_{TG} is the turbine generator unit gross power (MW_e), and N_{TG} is the number of turbine generator units.

Account 23.02: Not used.

Account 23.03: Condensing System (condensers, steam packing exhauster, condensate system, condenser-gas removal system, turbine bypass system and condensate polishing system).

$$C_{CS} = 36.05 \left(\frac{Q_{REJ}}{2253} \right)^{0.9} \quad (\text{M\$}) , \quad (7-33)$$

where Q_{REJ} is the heat rejected (MW_t).

Account 23.04: Feedheating System (feedwater heaters, feedwater pumps and drives, and extraction steam system).

$$C_{FS} = 23.84 \left(\frac{P_t}{3800} \right)^{0.6} \quad (\text{M\$}) , \quad (7-34)$$

where P_t is the power cycle total thermal power (MW_t).

Account 23.05: Other Turbine Plant Equipment (main vapor piping system, closed cooling-water system for turbine building, demineralized water make-up system, chemical treatment system, and neutralization system).

$$C_{OTPE} = 23.87 \left(\frac{P_{TG}}{1547} \right)^{0.6} N_{TG} \quad (\text{M\$}) , \quad (7-35)$$

Account 23.06: Turbine Plant Instrumentation and Control (turbine plant control board, panels, cabinets, and racks, and process computer).

$$C_{TPIC} = 5.82 \left(\frac{P_{TG}}{1547} \right)^{0.3} N_{TG} \quad (\text{M\$}) , \quad (7-36)$$

Account 23.07: Turbine Plant Miscellaneous Items.

$$C_{TPMI} = 7.72 \left(\frac{P_{TG}}{1547} \right)^{0.8} N_{TG} \quad (\text{M\$}) . \quad (7-37)$$

All cost coefficients are in January 1, 1983 dollars (M\$) and represent the costs for a mature (1990s) industry.

7.5 ELECTRIC PLANT EQUIPMENT (ACCOUNT 24)

The electric plant equipment conveys the electric power generated in the plant to the low-voltage bushings of the generator step-up (GSU) transformers, controls and meters the electric energy, and protects the components through which the power flows. It is the source of power for the plant auxiliaries, for the plant control, protection and surveillance systems during normal operation, and for the plant protection system and engineered safety features during normal operation, abnormal conditions, and accident conditions.

For the Cascade reactor, the electric plant equipment cost scales as

$$C_{EPE} = 70.6 (P_e/905)^{0.38} \quad (\text{M\$}) , \quad (7-38)$$

where P_g is the gross electric power in MW_e . The numerical coefficients in Eq. (7-38) are the point-design values of cost in 1985 dollars and the gross electric power.⁵

For the other reactor concepts, Account 24 is divided into six subaccounts, each described below. The account breakdown follows that given in Ref. 1. The scaling exponent as given by Ref. 27 is $\alpha = 1.0$, whereas Ref. 3 gives a value of $\alpha = 0.4$. We chose to use the values given in Ref. 3 when available, and those from Ref. 27 when Ref. 3 values are not available. All cost coefficients are in January 1, 1983 dollars (M\$) and represent the costs for a mature (1990s) industry.

Account 24.01 Switchgear (generator load-break switch and station-service switchgear).

$$C_{\text{SWGR}} = 12.367 \left(\frac{P_{\text{TG}} N_{\text{TG}}}{1547} \right)^{0.4} \quad (\text{M\$}) , \quad (7-39)$$

where P_{TG} is turbine generator unit gross power (MW_e), and N_{TG} is number of turbine generator units.

Account 24.02 Station-Service Equipment (station-service and start-up transformers, unit substations, and auxiliary power sources).

$$C_{\text{SSE}} = 18.661 \left(\frac{P_{\text{TG}} N_{\text{TG}}}{1547} \right)^{0.4} \quad (\text{M\$}) , \quad (7-40)$$

Account 24.03 Switchboards (control panels and auxiliary power and signal boards).

$$C_{\text{SWB}} = 1.830 \left(\frac{P_{\text{TG}} N_{\text{TG}}}{1547} \right)^{0.4} \quad (\text{M\$}) , \quad (7-41)$$

Account 24.04: Protective equipment (general station grounding, lightning protection, cathodic protection, and heat tracing and freeze protection systems).

$$C_{\text{PE}} = 3.75 \left(\frac{A_{\text{BLDG}}}{25,000} \right) \quad (\text{M\$}) \quad (7-42)$$

where A_{BLDG} is the total building area (all buildings) (m^2).

Account 24.05: Electric Structures and Wiring Containers (underground duct runs and conduit and cable raceways).

$$C_{ESWC} = 26.78 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.4} \quad (\text{M\$}) , \quad (7-43)$$

Account 24.06: Power and Control Wiring (main generator bus duct, power wiring, control cable and instrument wire, and containment penetrations).

$$C_{PCW} = 23.06 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.4} \quad (\text{M\$}) . \quad (7-44)$$

7.6 MISCELLANEOUS PLANT EQUIPMENT (ACCOUNT 25)

The miscellaneous plant equipment includes the systems and components for maintenance, plant start-up, or general supply of plant equipment requirements. Included are the cranes and hoists; air, water, and steam services; auxiliary boiler and associated equipment; plant fuel-oil system; and various on- and off-site environmental monitoring systems.

For the Cascade reactor, the miscellaneous plant equipment cost scales as

$$C_{MPE} = 16.3 (P_t/1670)^{0.18} \quad (\text{M\$}) , \quad (7-45)$$

where P_t is the total thermal power in MW_t (Ref.5).

For the other reactor concepts, Account 25 is divided into five subaccounts, each described below. The account breakdown follows that given in Ref. 1. All cost coefficients are in January 1, 1983 dollars (M\$) and represent the costs for a mature (1990s) industry.

Account 25.01: Transportation and Lifting Equipment (major cranes and other cranes and hoists).

$$C_{TLE} = 5.90 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.30} \quad (\text{M\$}) , \quad (7-46)$$

where P_{TG} is the turbine generator unit gross power (MW_e), and N_{TG} is the number of turbine generator units.

Account 25.02: Air, Water and Steam Services Systems (compressed air systems, service water system, normal fire protection system, sodium fire protection

system, portable water system, auxiliary steam system, process chilled water system, and plant fuel-oil storage tank).

$$C_{AWSSS} = 34.78 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.30} \quad (\text{M\$}) \quad (7-47)$$

Account 25.03: Communications Systems (local communications system, fire detection system, and security system).

$$C_{CS} = 7.92 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.30} \quad (\text{M\$}) \quad (7-48)$$

Account 25.04: Furnishing and Fixtures (instrument shop apparatus, off-site radiological monitoring system, meteorological monitoring system, water quality monitoring system, thermal effluent monitoring system, seismic monitoring system, and other furnishings and fixtures).

$$C_{FF} = 2.82 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.30} \quad (\text{M\$}) \quad (7-49)$$

Account 25.05: Waste Water Treatment Equipment.

$$C_{WWTE} = 3.13 \left(\frac{P_{TG} N_{TG}}{1547} \right)^{0.30} \quad (\text{M\$}) \quad (7-50)$$

7.7 MAIN HEAT-REJECTION SYSTEM (ACCOUNT 26)

The main heat-rejection system includes a closed-loop circulating water system. It consists of buildings, structures, and mechanical equipment needed to reject the plant excess heat through mechanical or natural draft wet cooling towers.

For Cascade, the cost of the main heat-rejection system scales as

$$C_{MHRS} = 21.5 (P_t / 1670)^{0.86} \quad (\text{M\$}) \quad (7-51)$$

where P_t is the total thermal power in MW_t (Ref. 5).

For the other reactor concepts, Account 26 is divided into two subaccounts, each described below. The account breakdown follows that given in Ref. 1. All costs are in January 1, 1983 dollars (M\$).

Account 26.01: Structures (makeup water intake and discharge structures, circulating water pump house, makeup water pretreatment building, and cooling tower switchgear building).

$$C_{STRS} = 3.05 \left(\frac{Q_{REJ}}{2253} \right)^{0.80} \quad (M\$) \quad (7-52)$$

where Q_{REJ} is heat rejected (MW_t).

Account 26.02: Mechanical Equipment (circulating water pumps, cooling towers and cooling tower basins, main cooling-tower makeup and blowdown systems, and makeup pretreatment plant).

$$C_{ME} = 35.25 \left(\frac{Q_{REJ}}{2253} \right)^{0.80} \quad (M\$) \quad (7-53)$$

7.8 DRIVER EQUIPMENT (ACCOUNT 27)

The SAFIRE code allows any driver type to be used with any reactor concept, but normally a KrF laser is used with the HYLIFE and Cascade reactors, an rf linac with the HIBALL reactor, and a LIB-generating pulsed-power diode with the EAGLE reactor. The driver cost algorithms are not taken from the point-design studies but from more recent costing efforts. The costing studies were conducted by different groups that made independent assumptions, and comparisons between absolute values should be made cautiously.

7.8.1 KrF-Laser Costing

The KrF-laser costing algorithm is based on a system of multiplexed 200-kJ amplifiers and an optical train with 4 J/cm^2 fluence limits. Cost typically scales strongly with driver energy, moderately with repetition rate, and weakly with pulse length. The algorithm is¹⁴

$$C_d = C_{d0} (E_d/E_{d0})^\alpha \exp [\beta(W_d/W_{d0})] \exp [f(E_d/E_{d0})(\tau_{d0}/\tau_d - 1)] , \quad (7-54)$$

where

- C_{d0} = reference cost (\$150 million),
- E_{d0} = reference driver energy (1 MJ),
- α = scaling coefficient (0.74),

$$\begin{aligned}\beta &= \text{constant (0.024)}, \\ W_{d0} &= \text{reference repetition rate (1 Hz)}, \\ \tau_{d0} &= \text{reference pulse length (10 ns)}, \\ f(E_d/E_{d0}) &= 0.05 + 0.001(E_d/E_{d0}).\end{aligned}$$

The cost given by Eq. (7-54) is in 1984 dollars and reflects what was assessed to be near-term technology. Although a large part of the laser consists of identical modules, the scaling factor α is less than unity to reflect quantity discounts and a construction learning curve. This dependence is shown in Fig. 7-1(a). The scaling with repetition rate reflects the dependence on gas recirculation power and heat-exchanger scaling, and is reflected in Fig. 7-1(b). The scaling with pulse length, shown in Fig. 7-1(c), is the result of the greater number of small-sized optics required for optical methods of pulse compression.

7.8.2 Heavy-Ion Driver Costing

The form of the costing algorithm used here for heavy-ion drivers has traditionally been used for both rf and induction linacs. Assuming that induction technology is ultimately cheaper than rf for the same output parameters, we use coefficients that correspond to the former technology. In the study on which the coefficients are based, the algorithm is¹⁵

$$C_d = C_{d0} E_d^\alpha, \quad (7-55)$$

where C_{d0} is the reference cost (\$680 million), E_d is the driver energy (MJ), and α is the scaling factor (0.4). The costs are given in 1984 dollars and represent advances from present day technology, such as use of multiple beams, electrostatic focusing at low energies, higher tune shift, and a decrease in injector emittance. Present day costs could be 50 to 100% higher. The scaling factor again represents quantity discounts. Apparently a greater discount is expected than for KrF lasers.

7.8.3 Light-Ion Driver Costing

Comparatively little literature has been published on the cost of a commercial pulsed-power, diode-generated, light-ion driver. Nevertheless, the

Figure 7-1. Driver cost as a function of (a) energy, (b) repetition rate, and (c) pulse length.

cost can be assessed if it is assumed the physics issues of generating a high-quality beam at the diode are not influencing factors. The scaling relationship accounts for the fact that for a given energy on target, the energy required at the diode is a function of the chamber radius [see Eq. (2-3)]. The coefficients have been generated as a result of discussions with personnel at Sandia National Laboratories,¹⁶ and are

$$C_d = C_{d0} \left(\frac{E_d}{1 - 0.075R} \right)^\alpha, \quad (7-56)$$

where α is the scaling factor (0.8), and where C_{d0} is quoted in 1979 dollars.

7.9 TARGET FACTORY EQUIPMENT (ACCOUNT 28)

The target-factory cost estimate used in the SAFIRE code is based on a production scheme consisting of a shell-fabrication and DT-fill subsystem, a coating process subsystem, and a cryogenic subsystem. Figure 7-2 shows the model used. The cost is calculated as²⁸

$$C_{tf} = C_{tf0} (\omega/\omega_0)^{0.6} \times \left[\delta_1 (Y/Y_0)^{0.6\epsilon_1} + \delta_2 (Y/Y_0)^{0.6\epsilon_2} + \delta_3 (Y/Y_0)^{0.6\epsilon_3} \right] \text{ (M\$)}, \quad (7-57)$$

where

C_{tf0} = cost of a reference target factory (\$100 million),

ω = target repetition rate (Hz),

ω_0 = reference repetition rate (1 Hz),

Y = target yield (MJ),

Y_0 = a reference target yield (100 MJ),

$\delta_1, \delta_2, \delta_3$ = subsystem cost fraction (1/3, 1/3, 1/3, respectively),

$\epsilon_1, \epsilon_2, \epsilon_3$ = scaling exponents (1, 1/3, 1/3, respectively).

The default values of the reference coefficients are given in parentheses. The coefficients assume that a target factory producing 600-MJ targets at 5 Hz costs \$100 million in 1983 dollars. The subsystem costs are assumed to be divided equally between the three subsystems. The motivation for setting ϵ_1 to unity is that the shell fabrication and DT-fill processes are

Figure 7-2. Target factory schematic flow diagram.

Figure 7-3. Relative target cost as a function of production rate.

assumed to be proportional to the target fuel mass. The coating process and subsequent cryogenic handling are assumed to be proportional to the fuel radius. Since the yield is proportional to fuel volume, it follows that

$$\epsilon_2 = \epsilon_3 = 1/3.$$

The results of using Eq. (7-57) are illustrated in Fig. 7-3 for the case of constant fusion power. It is important to realize that Eq. (7-57) assumes a fixed number of process lines. Variations in process lines can be accounted for using the more detailed equations given in Ref. 28. It should also be realized that the cost given by Eq. (7-57) does not include material makeup or maintenance cost.

7.10 INFLATION FACTORS

Because all components are costed relative to some reference year, it is necessary to adjust the costs to the year of interest. The adjusted cost is given by

$$C_a = C \prod_{n=r}^a (1 + i_n), \quad (7-58)$$

where

- C = component cost,
- r = reference year,
- a = adjusted year,
- i = annual inflation factor.

The symbol Π implies multiplication over the number of years between r and a if $a > r$. The inflation factors used are listed in Table 7-2.

Table 7-2. Inflation factors.

Year	Inflation factors ^a
1975	0.093
1976	0.052
1977	0.059
1978	0.074
1979	0.086
1980	0.093
1981	0.094
1982	0.063
1983	0.038
1984	0.037
1985	0.030

^a Based on Gross National Product implicit price deflator.³

8. TOTAL CAPITAL COSTS

8.1 TOTAL DIRECT COSTS

The total direct cost is given by

$$TDC = \sum_{i=20}^{28} C_i \quad (8-1)$$

where C_i is the direct capital cost of account i , adjusted to a reference year.

8.2 TOTAL INDIRECT COSTS

The indirect capital cost accounts are given by^{29,4}

$$C_{9i} = f_{9i} TDC \quad (\text{M\$}) , \quad (8-2)$$

where C_{9i} is an indirect cost account, f_{9i} is an indirect cost fraction, and i is an index ranging from 1 to 4. Table 8-1 gives the indirect cost accounts and costing fractions. The sum of Accounts 91 to 94 is the total indirect cost, TIC.

The plant contingency is calculated as a fraction of the sum of the direct plus indirect costs. Thus,

$$C_{95} = f_{95} (TDC + TIC) \quad (\text{M\$}) , \quad (8-3)$$

Table 8-1. Indirect cost accounts and fractions.

Account No.	Account title	Fraction f_{9i}
91	Construction Services and Equipment	0.20
92	Home Office Engineering and Service	0.15
93	Field Office Engineering and Service	0.10
94	Owner's Cost	0.07
95	Contingency	0.10

where C_{95} is the contingency amount, and f_{95} is the contingency fraction. The contingency fraction is also given in Table 8-1.

The total overnight construction cost TOC, used later in evaluating the total capital cost and maintenance expense, is given by

$$TOC = (1 + f_{91} + f_{92} + f_{93} + f_{94}) (1 + f_{95}) TOC . \quad (8-4)$$

8.3 TIME-RELATED COSTS

The time-related cost accounts consist of

$$\text{Escalation during construction (Account 96)} = f_{EDC} TOC, \quad (8-5)$$

$$\text{Interest during construction (Account 97)} = f_{IDC} TOC. \quad (8-6)$$

The factors f_{EDC} and f_{IDC} are evaluated according to either constant- or current-dollar analysis. For current-dollar analysis,^{4,30}

$$f_{EDC} = (1 + e)^{0.6\tau} - 1, \quad (8-7)$$

and

$$f_{IDC} = (1 + e)^{0.6\tau} [(1 + x)^{0.4\tau} - 1], \quad (8-8)$$

where x is the effective after-tax cost of money, e is the escalation rate, and τ is the construction period (yr). For a constant-dollar analysis, which assumes the purchasing power of the dollar remains constant, Eqs. (8-7) and (8-8) are again used but the effective after-tax cost of money x is replaced by the real cost of money x_r , and the escalation rate e is replaced by the real escalation rate e_r , where

$$e_r = (1 + e)/(1 + i) - 1, \quad (8-9)$$

$$x_r = (1 + x)/(1 + i) - 1, \quad (8-10)$$

and i is the general inflation rate. Note that if the plant cost escalates at the same rate as inflation, then $f_{EDC} = 0$ and

$$f_{IDC} = (1 + x_r)^{0.4\tau} - 1$$

for the constant-dollar analysis.

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 is tax deductible. It is calculated as^{29,4}

$$x = i_c f_c + i_p f_p + (1 - t) i_d f_d, \quad (8-11)$$

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,
- f_d = fraction of capital from debt,
- t = effective income tax rate (state and federal).

The default values used in the SAFIRE code for the parameters defined above are listed in Table 8-2 (Refs. 29 and 4).

Table 8-2. Default parameters used in the SAFIRE code for parameters defined in Eq. (8-11).

Parameter	Symbol	Default value
Rate of return on common stock	i_c	14%
Fraction of capital from common stock	f_c	38%
Rate of return from preferred stock	i_p	9%
Fraction of capital from preferred stock	f_p	12%
Interest rate on debt	i_d	10%
Fraction of capital from debt	f_d	50%
General inflation rate	i	6%
Cost escalation rate (all items)	e	6%
Income tax rate (state and federal)	t	48%
Construction period	τ	8 yr

8.4 MULTI-UNIT POWER PLANTS

An ICF power plant can have up to four individual units. A unit can be described as an electricity-producing system dependent only on one or more outside target factories and drivers, which are shared among all the units. Besides sharing the target factory and driver costs, there are additional cost savings associated with multi-unit power plants. The additional cost savings are associated with series construction and can be described as follows.⁴

• Direct costs--The total direct costs of N_u units are C_{dt}
 $= C_{d1}(0.2 + 0.8N_u)$, where C_{dt} are the total direct costs and C_{d1} are the direct costs of the first unit. This adjustment applies to Accounts 20 to 26.

• Indirect costs--The indirect capital costs of N_u units are C_{it}
 $= C_{i1}(0.4 + 0.6N_u)$, where C_{it} are the total indirect capital costs and C_{i1} are the indirect capital costs of the first unit. This adjustment applies to Accounts 91 to 94.

Note that the direct cost of the second through fourth units is 80% of the first, and the indirect cost of the additional units is 60% of the first.

9. COST OF ELECTRICITY

The COE is calculated as

$$\text{COE} = \frac{R(\text{TCC}) + M + F}{0.0876 P_n \alpha} \quad (\$/\text{kW}_e \cdot \text{h}) , \quad (9-1)$$

where

- R = annual fixed charge rate on capital (yr^{-1}),
- TCC = total capital cost of the plant (M\$),
- M = annual operation and maintenance cost (M\$),
- F = annual fuel cycle cost (M\$),
- P_n = net electric power (MW_e),
- α = availability fraction (0.7).

The default value for the availability is given in parentheses. All other factors are computed as described above. The SAFIRE code can calculate these factors based on either constant- or current-dollar analysis.

9.1 FIXED CHARGE RATE

The fixed charge rate R is calculated for current-dollar analysis as^{29,4}

$$R = \frac{Ck - td}{1 - t} + t_p + r , \quad (9-2)$$

where

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

In evaluating Eq. (9-1) the capital recovery factor is given by^{29,4}

$$C(x, N) = \frac{x(1-x)^N}{(1+x)^N - 1} , \quad (9-3)$$

where N is the plant life in years.

The levelized tax depreciation is calculated assuming accelerated depreciation will be used; hence

$$d = C(x, N) \sum_n \frac{(1+x)^{-0.4\tau} d(n)}{(1+x)^n} \quad (9-4)$$

The numerator on the right-hand side of Eq. (9-4) represents the fraction of initial investment depreciable for tax purposes. Table 9-1 lists the tax depreciation deduction fraction $d(n)$ in year n . In evaluating Eqs. (9-2) through (9-4) the SAFIRE code uses default values of $N = 30$ yr, $r = 0.01$, and $t_p = 0.02$.

For constant-dollar analysis the fixed charge rate is adjusted to reflect the real (inflation free) cost of money. The constant dollar fixed charge rate is then given by

$$R_0 = R \frac{C(x_r, N)}{C(x, N)}, \quad (9-5)$$

where R is from Eq. (9-2) and $C(x_r, N)$ and $C(x, N)$ are calculated from Eq. (9-3). The constant-dollar analysis accounts for the fact that items such as property tax that do not change with time are decreasing in reference-year dollars.

Table 9-1. Values for tax depreciation deduction fraction, $d(n)$.

Year n	Ten-year property (nuclear) (%)
1	8
2	14
3	12
4	10
5	10
6	10
7	9
8	9
9	9
10	9

9.2 ANNUAL MAINTENANCE COSTS

It is assumed that operation and maintenance costs M are proportioned to the TOC and escalate at the same rate as general inflation. For constant-dollar analysis the levelized costs are equal to those in reference-year dollars and

$$M_0 = f_m (\text{TOC}), \quad (9-6)$$

where f_m is a suitable fraction. The SAFIRE code assumes a default value of $f_m = 0.03$.

For current-dollar analysis the cost is related to the levelized cost by

$$M = [f_m (\text{TOC})(1+i)^T C(x,N)]/C(x_r,N). \quad (9-7)$$

The quantity $(1+i)^T$ inflates the cost from reference-year dollars (the reference year is the year that construction starts) to dollars in the year of initial operation. The factor $C(x,N)/C(x_r,N)$ is a levelizing factor for operation and maintenance costs that increase over the N -year plant life.

9.3 ANNUAL FUEL COSTS

Only consumable target materials--deuterium and lithium--are costed in the SAFIRE code. The annual fuel costs are calculated as the product of the mass consumed times the cost per unit mass. For deuterium the mass consumption rate is given by

$$\begin{aligned} \dot{m}_d &= \left(\frac{2.014 \text{ g}}{6.02 \times 10^{23} \text{ reactions}} \right) \left(\frac{1 \text{ reaction}}{17.6 \text{ MeV}} \right) \left(\frac{1 \text{ MeV}}{1.6 \times 10^{-19} \text{ MW}_f \cdot \text{s}} \right) \\ &\quad \times \left(\frac{3.154 \times 10^7 \text{ s}}{\text{yr}} \right), \quad (9-8) \\ &= 37.5 \text{ g/MW}_f \cdot \text{yr}, \end{aligned}$$

where the subscript f refers to fusion power. The lithium consumption is calculated by assuming one reaction with ${}^6\text{Li}$ per D-T fusion reaction. Hence,

$$\dot{m}_{\text{Li-6}} = 112 \text{ g/MW}_f \cdot \text{yr},$$

where T_6 is the ${}^6\text{Li}$ breeding ratio. Converting to grams of natural lithium yields

$$\dot{m}_{\text{Li}} = 1740 T_6 \text{ (g/MW}_f\text{·yr)}. \quad (9-9)$$

The fuel cost is written as

$$F_0 = P_f \alpha (1.74 T_6 U_{\text{Li}} + 0.037 U_0) \quad (\$), \quad (9-10)$$

where

P_f = plant power (MW),

α = plant factor,

U_{Li} = unit cost of lithium (\$/kg),

U_0 = unit cost of deuterium (\$/kg).

For purposes of evaluating F_0 , the factor T_6 is set to unity in the SAFIRE code. The cost of deuterium is taken as \$5600/kg in 1985 dollars.³¹ The cost of lithium is taken as \$44/kg in 1985 dollars.³¹

Equation (9-10) is the constant-dollar fuel cost. The current-dollar cost is given by

$$F = [F_0(1 + i)^T C(x, N)] / C(x_f, N), \quad (9-11)$$

where the multiplying factors are the same as those used for the current-dollar analysis of maintenance costs.

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