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Multi-Unit Inertial Fusion Plants Based on HYLIFE-II, With Shared Heavy-Ion RIA Driver and Target Factory, Producing Electricity and Hydrogen Fuel.

IFEFUEL5: An IFEFUEL MathCAD systems code for multi-unit HYLIFE-II plants

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I. INTRODUCTION

Following is a modification of the IFEFUEL systems code⁽¹⁾, called IFEFUEL2, to treat specifically the HYLIFE-II target chamber concept⁽²⁾. The same improved Recirculating Induction Accelerator (RIA) energy scaling model developed recently by Bieri (May 1993 version) is used in this survey of the economics of multi-unit IFE plants producing both electricity and hydrogen fuel. Reference cases will assume conventional HI-indirect target gains for a 2 mm spot, , and improved HYLIFE-II BoP models as per Hoffman⁽³⁾. Credits for improved plant availability and lower operating costs due to HYLIFE-II's 30-yr target chamber lifetime are included, as well as unit cost reductions suggested by Delene to credit greater "learning curve" benefits for the duplicated portions of a multi-unit plant.

To illustrate the potential impact of more advanced assumptions, additional "advanced" cases will consider the possible benefits of an MHD + Steam BoP, where direct MHD conversion of plasma from baseball-size LiH target blanket shells⁽⁴⁾ is assumed to be possible in a new (as yet undesigned) liquid Flibe-walled target chamber, together and separately, with advanced, higher-gain heavy-ion targets with Fast Ignitors⁽⁵⁾. These runs may help decide the course of a possible future "HYLIFE-III" IFE study.

Beam switchyard and final focusing system costs per target chamber are assumed to be consistent with single-sided illumination, for either "conventional" or "advanced" indirect target gain assumptions. Target costs are scaled according to the model by Woodworth⁽⁶⁾. In all cases, the driver energy and rep rate for each chosen number of target chambers and total plant output will be optimized to minimize the cost of electricity (CoE) and the associated cost of hydrogen (CoH), using a relationship between CoE and CoH to be presented in the next section.

REFERENCES

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- (4) B. G. Logan, "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD conversion", *Fusion Engineering and Design* 22, p. 151, (1993)
- (5) M. Tabak, "Ignition and High Gain with Ultra-Powerful Lasers" Nov. 1993 APS Division of Plasma Physics invited paper, to be published in *Physics of Fluids*.
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II. UNIT COST OF HYDROGEN PRODUCTION, STORAGE, TRANSPORT/COMPRESSION VS COE

For $ip := 1..50$ points along the CoE axis, we plot, for 1993 \$,

Cost of Electricity (cents/kWehr):	$Cost_of_electricity_{ip} := 0.1 \cdot ip$
Delivered Cost of H_2 (no tax) (\$/GJ):	$CoH_2(CoE) := 3.2 + 3.38 \cdot CoE$
Production of H_2 (\$/GJ):	$PoH_2(CoE) := 1.2 + 3.08 \cdot CoE$
Storage of H_2 (\$/GJ):	$SoH_2(CoE) := 1 + 0.3 \cdot CoE$
Transport/compression of H_2 (\$/GJ):	$ToH_2(CoE) := 1$

[Methodology and commentary in this section follows the work of Heidrich and Pettibone. The data for this Fig.1 was obtained from H.J. Plass,Jr, et. al."Economics of Hydrogen as a Fuel for Surface Transportation", but adjusted for recent advances in electrolysis cell efficiencies from 70% to 80%.]

Fig. 1 The unit cost (\$/GJ) of delivered hydrogen (excluding taxes) produced by 80 % efficient electrolysis as a function of the cost of electricity in cents per kWehr, and the contributing component costs of electrolysis, storage, and transport / compression. Equivalent passenger miles per unit of H_2 energy would be twice as high as for gasoline engines, because hydrogen fuel cells or hydrogen-optimized internal combustion engines are twice as efficient as gasoline engines. A 10 GWe water electrolysis plant produces hydrogen energy at a rate equivalent to a 100,000 barrel/day oil refinery, but supports as many hydrogen-powered cars as a 200,000 bbl/day oil refinery supports gasoline cars. A $CoH \sim 13.4$ \$/GJ (delivered, excluding taxes), corresponding to $CoE \sim 3$ cents/ kWehr, is required to provide equal consumer fuel cost per passenger mile with 45 % efficient-hydrogen-optimized cars as for 25 % efficient gasoline powered cars, assuming equal taxes per mile and no special hydrogen subsidies. Thus, the combination of HYLIFE-II benefits of no-first-wall replacement, together with cost reductions with multi-unit IFE plants through economy of scale and economy of shared equipment, must reduce CoE from that of previous single 1 GWe IFE plants (~ 6 cts/kWehr) by a factor of about two, to produce competitive hydrogen in a future era of scarce natural gas.

III. MULTI-UNIT PLANT COSTING

For the following cases with $i = 1 \dots 4$, the total number of fusion chamber units/driver is: $Nu_i := 2^{i-1}$

For any system replicated Nu times, Delene has suggested the direct cost of Nu -units of the same system or sub-system to be given by $cd(Nu)$ times the direct cost of the first unit, where

Direct cost multiplier $cd(Nu) := \left[0.2 + 0.8 \cdot Nu \cdot 0.97^{\left(\frac{\ln(Nu)}{\ln(2)} \right)} \right]$

For	Nu_i	$cd(Nu_i) \cdot (Nu_i)^{-1}$
1	1	1
2	2	0.88
3	4	0.8
4	8	0.76

This will be used as a multi-unit direct cost factor for all Nu -replicated systems in multi-unit plants. All direct costs will be multiplied by a factor

Indirect cost multiplier $IDC := 1.936$ to obtain total capital costs.

units, Rel.direct cost per unit

The direct cost credits for multi-units will be used later on to multiply single unit subsystem costs which will contain the economy-of-scale dependence for the individual unit sizes. These credits suggested by Delene show the biggest % reduction (16%) for the first doubling, from one to two units, with much smaller reductions (eg, 9% more) for the second doubling, going from 2 to 4 units, even less going to 8 units. These credits are assumed to apply to all replicated systems such as the target chambers and steam plants, but not to a single driver and target factory.

For cases with the highest $P_{net}(\text{one unit}) = 2000 \text{ MWe}$, there are two Steam Power Plants (SPP) per fusion chamber-unit, which will have additional cost reductions by a factor of $(1 - f_{\text{savings}})$, with a value for f_{savings} given below.

Credit for no first wall replacement shared O&M services in a multi-unit plant (as per Delene)

We reduce the usual O&M costs of 6 % of direct costs by a factor of two to credit the fact that liquid walls in HYLIFE-II should reduce O&M costs relative to fission plants and other fusion concepts requiring regular first wall-replacement. Also, because of shared facilities, maintenance, S&E, QA, rad waste and security, multi-unit O&M costs are also reduced from those for a single unit, by using the total plant net electric power instead of the net power per unit in the the usual $1/\sqrt{P_{net}}$ scaling.

Fuel charges (Lithium 6): $CoE_{FUEL} := 0.0032 \cdot 1.3216$ (cts/kWehr) escalated to 1993\$

Decommissioning charges: $CoE_{DECOM} := 0.1 \cdot 1.1$ (cts/kWehr) escalated to 1993\$

Total plant net electric power cases evaluated: For $k = 1 \dots 4$ cases with different size net power per fusion chamber units:

Chose net electric outputs per reactor unit: $Peu_1 := 250$ $Peu_2 := 500$ $Peu_3 := 1000$ $Peu_4 := 2000$ (MWe/ unit),
giving total plant outputs: $Pn_{i,k} := Nu_i \cdot Peu_k$ (MWe/plant)

Table 1: Total plant net power cases considered (in MWe) :	For $P_{eu} =$	250	500	1000	2000	MWe / unit, and
	$P_n =$	250	500	1000	2000	1
		500	1000	2000	4000	2
		1000	2000	4000	8000	4
		2000	4000	8000	16000	8
					# (Nu)	
						units per plant

Plant availability factor: $Fa := 0.85$

For HYLIFE-II, we credit all-liquid wall target chamber (no need to replace solid first wall or blanket materials, by raising the average plant capacity factor from the usual 0.75 to 0.85, the latter value having been achieved in a few nuclear plants.

Nuclear grade cost multiplier: $CF_{NS} := 1.5$ Following Hoffman (3), costs for HYLIFE-II subsystems which must be nuclear grade will have this explicit cost multiplier.

IV. SYSTEM PERFORMANCE ASSUMPTIONS

Direct Conversion topping cycle efficiency ⁽⁴⁾ :	$\eta_{DC} := 0.52$	< reduced from 55 % for losses extracting 20% of the LiH working fluid captured into Flibe @ 15 kcal/mole.
Thermal Steam Cycle <u>Net</u> Efficiency ⁽³⁾ :	$\eta_{spp} := 0.43$	< highest performance <u>subcritical</u> steam cycle
Blanket fusion energy multiplication:	$M := 1.18$	< for Flibe; advanced Flibe + Li shell cases assumed to be the same for MHD+steam combined cycles.
HYLIFE-II pump efficiency ⁽²⁾ :	$\eta_p := 0.80$	< recirculating pump power and driver power will be computed in the coming sections
Other plant auxiliary power fraction:	$f_{aux} := 0.0072$	< multiplies the thermal power; gives 18 MW for 2500 MWth, as in HYLIFE-II baseline.
Cost reduction factor for two SPP's per unit:	$f_{savings} := 0.12$	

Indirect Drive Target fusion gains and yields for "Conventional" (Lindl) and "Advanced" (Tabak) indirect-drive :

Vary driver energy as the primary optimization variable: For $j := 1..61$ $Ed_j := 0.45 + 0.05 \cdot j^{1.4}$ (MJ)

"Conventional gains"- (Moir's fit to HI "median for 2 mm spot size)

$$G(Ed) := \Phi(Ed - 2.51) \cdot (-94.6137 + 60.7426 \cdot Ed - 7.7764 \cdot Ed^2 + 0.509 \cdot Ed^3 - 0.0122 \cdot Ed^4) + 15 \cdot \Phi(2.5 - Ed)$$

This form sets $G_{min} = 15$ for $Ed < 2.5$ to avoid power balance solver hangups at low Ed . This is only for computational convenience of MathCAD, which must solve every case in a matrix. Solutions will thus only be valid for $Ed > 2.5$ MJ for conventional gains, but CoE minimization will always pick $Ed > 2.5$ MJ anyway.

"Conventional" yields corresponding to "conventional" gains are $Y(Ed) := Ed \cdot G(Ed)$ (MJ), similarly,

"Advanced gains" $G_a(Ed) := 200 \cdot (Ed - 0.45)^{0.4}$ give "advanced" yields $Y_a(Ed) := Ed \cdot G_a(Ed)$ (MJ)

Fig.2 Assumed indirect-drive target gains (a) and yields (b) for conventional ("conv") and advanced ("adv") targets. "Conventional" curves represent HYLIFE-II gain curves for heavy-ion targets with a 2 mm radius spot size ; "Advanced" represents a heavy-ion target enhanced with the "Fast Ignitor"⁵.

Heavy-Ion Driver efficiency as a function of driver energy : $\eta_{HI}(Ed) := 0.35 \cdot (Ed \cdot 4^{-1})^{0.25}$

Fig. 3 Driver efficiency as a function of driver energy for heavy-ion drivers (Bieri). This efficiency improving with driver energy E_d reflects a finite accelerator power consumption, even with zero beam current running through the induction cores.

V. CALCULATION OF ENERGY CAPTURE FRACTION OF TARGET BLANKET SHELLS FOR MHD CONVERSION

[This section has no effect on the "conventional" baseline cases, but is used for later "advanced" cases; skip to the next section VI to continue with calculation of recirculating power fraction for baseline cases]

Initial cavity stagnation pressure : $patmo := 25$ (bar) $pco := patmo \cdot 10^5$ (in Pascals)

Specified fusion cavity plasma stagnation temperature: $Tco := 12000$ (degK)

LiH working shell material mass density: $mds := 830$ (kg/m3)

The transfer pressure ratio from target chambers to a common plasma accumulation chamber: $prpc := 5$ < a fraction $prpc^{-1} \sim 20\%$ of the LiH target shell material mixes with the Flibe.

Table 2 : Properties of lithium-hydride working fluid for the target blanket shells with 0.2 % aluminum structure:

	Element 1 - (Li)	Element 2 - (H)	Element 3 - (Al)	
Atomic fractions	$mfo1 := 0.499$	$mfo2 := 0.499$	$mfo3 := 0.002$	
Ionization energy	$I1 := 5.39 \cdot 11600$	$I2 := 13.53 \cdot 11600$	$I3 := 5.96 \cdot 11600$	(equiv. deg K)
Molar mass	$m1 := 0.007$	$m2 := 0.001$	$m3 := 0.02$	(kg/gram-atom)
Mixture atomic molar mass (kg/gram-atom)	$mo := 0.0044$			(kg/gram-atom)
Vapor saturation temperature (degK)	$Ts := 1100$			(deg K)
Specific enthalpy, 300degK to Ts (MJ/kg)	$hs := 18 \cdot 10^6$			(j/kg)
Minimum MHD generator exhaust temp.(deg K)	$Tgx := 3000$			(deg K)
Nozzle coolant (lithium) molar mass (kg/gm-atom)	$mb := 0.007$			(kg/gram-atom)
Nozzle coolant (lithium) ionization energy	$Ib := 5.39 \cdot 11600$			(equiv. deg K)

DEFINITION OF MOLAR FRACTIONS: (local f = accumulated wall coolant mass flow/target mass flow)

Molar fraction of species mfo : $mf(mfo, f) := mfo \cdot mb \cdot (mb + f \cdot mo)^{-1}$

Molar fraction of wall coolant species: $mfb(f) := f \cdot mo \cdot (mb + f \cdot mo)^{-1}$

Local mixture molar mass : $m(f) := mo \cdot mb \cdot (1 + f) \cdot (mb + f \cdot mo)^{-1}$ (kg/gram-atom)

IONIZATION FORMULAS:

General SAHA coefficient : $C(T, p, I) := .033 \cdot \frac{T^{2.5}}{p} \cdot \exp\left(\frac{-I}{T}\right)$

Boundary layer
ionization fraction : $ab(T, p) := \sqrt{C(T, p, I_b) \cdot (1 + C(T, p, I_b))}^{-1}$

Ionization parameter,
Core-flow plasma : $af(T, p, f) := mf(mfo1, f) \cdot C(T, p, I1) + mf(mfo2, f) \cdot C(T, p, I2) \dots$
 $+ mf(mfo3, f) \cdot C(T, p, I3) + mfb(f) \cdot C(T, p, I_b)$

Simple ionization parameter
(when $a \ll 1$) : $afo(T, p, f) := (mf(mfo1, f) + mfb(f)) \cdot C(T, p, I1)$

Simple form of the total
core ionization function:
(when $a \ll 1$) $ao(T, p, f) := \sqrt{afo(T, p, f) \cdot (1 + afo(T, p, f))}^{-1}$

Ionization of component
elements in core plasma : $ai(T, p, f, I) := C(T, p, I) \cdot \left(\frac{1}{1 + \sqrt{1 + af(T, p, f)}} + C(T, p, I) \right)^{-1}$

More accurate form of the
core ionization fraction : $a(T, p, f) := mf(mfo1, f) \cdot ai(T, p, f, I1) + mf(mfo2, f) \cdot ai(T, p, f, I2) \dots$
 $+ mf(mfo3, f) \cdot ai(T, p, f, I3) + mfb(f) \cdot ai(T, p, f, I_b)$

ENTHALPY : Specific gas enthalpy (j/kg) of the core-flow plasma, including ionization :

$$h(T, p, f) := \left[((I1 + 2.5 \cdot (T - Ts)) \cdot ai(T, p, f, I1) + 2.5 \cdot (T - Ts) \cdot mf(mfo1, f) \dots) \cdot \frac{8.317}{m(f)} \right. \\ \left. + ((I2 + 2.5 \cdot (T - Ts)) \cdot ai(T, p, f, I2) + 2.5 \cdot (T - Ts) \cdot mf(mfo2, f) \dots) \right. \\ \left. + ((I3 + 2.5 \cdot (T - Ts)) \cdot ai(T, p, f, I3) + 2.5 \cdot (T - Ts) \cdot mf(mfo3, f) \dots) \right. \\ \left. + ((I_b + 2.5 \cdot (T - Ts)) \cdot ai(T, p, f, I_b) + 2.5 \cdot (T - Ts) \cdot mfb(f)) \right]$$

FRACTION OF FUSION YIELD CAPTURED BY LITHIUM-HYDRIDE TARGET SHELLS :

14 MeV neut. slowing down parameter: $Ls := 0.09$ (m) 14 MeV neut. inelastic energy loss parameter: $Es := 11$

14 MeV neut. absorb. length parameter: $La := 0.07$ (m) 14 MeV neutron energy multiplication in LiH: $M := 1.18$

Inner radius of the target shell : $rin := .01$ (m), $roa := rin \cdot La^{-1}$ $ro := rin \cdot Ls^{-1}$ (Normalized to La, Ls)

The fraction of slowed-down neutrons absorbed in a shell of normalized outer radius $ra = rout/La$:

$$fa(ra) := \left[\frac{\exp(ra) \cdot \exp(-roa) \cdot (roa + 1) - \exp(-ra) \cdot \exp(roa) \cdot (1 - roa) - 2 \cdot ra}{(\exp(ra) - \exp(-ra))} \right]$$

The fraction of fusion yield (inc. capture energy) captured in a shell of normalized outer radius $rs = rout/Ls$:

$$Fc(rs) := \frac{3.5 + 5 \cdot \exp(-(rs - ro)) + [Es + (M \cdot 14.1 - Es) \cdot fa(rs \cdot Ls \cdot La^{-1})] \cdot (1 - \exp(-(rs - ro)))}{17.6}$$

The above analytic formula for $F_c(rs)$ can be compared with Sahin's neutronics data "f" vs. r (for LiH) :

For $i = 1 \dots 8$ comparison points with Sahin's data:

$$fd_1 = .472 \quad fd_2 = .621 \quad fd_3 = .779 \quad fd_4 = .911 \quad fd_5 = 1.007 \quad fd_6 = 1.157 \quad fd_7 = 1.1765 \quad fd_8 = 1.177$$

$$rd_1 = 1 \quad rd_2 = 6 \quad rd_3 = 11 \quad rd_4 = 16 \quad rd_5 = 21 \quad rd_6 = 41 \quad rd_7 = 61 \quad rd_8 = 81$$

$$rst_1 := rd_1 \cdot (Ls \cdot 100)^{-1}$$

Fig. 4 This shows satisfactory agreement between the neutronics data (fd) and $F_c(rs)$ over the range of rd .

Next, the target blanket shell thickness rso corresponding to the chosen plasma temperature T_c is determined:

The total specific enthalpy to raise solid LiH to a plasma at temperature T_{co} is $ht := (h(T_{co}, p_{co}, 0) + hs)$

Trial guess of rso for the solver below:

$$rso := \left[\frac{10 \cdot 10^6 \cdot 1000}{4 \cdot \pi \cdot Ls^3 \cdot mds \cdot (h(T_{co}, p_{co}, 0) + hs)} + ro^3 \right]^{.333}$$

Given

$$ht \cdot \frac{4}{3} \cdot \pi \cdot (rso^3 - ro^3) \cdot Ls^3 \cdot mds = 10^6 \cdot Yo \cdot F_c(rso)$$

$$r_s(Yo) := \text{Find}(rso)$$

$$rs_j := r_s(Y(E_d_j)) \quad \text{"Conv." targets}$$

$$rsa_j := r_s(Ya(E_d_j)) \quad \text{"Advanced" targets}$$

The ideal shell capture fraction is

$$Fs_j := F_c(rs_j)$$

$$Fsa_j := F_c(rsa_j)$$

The outer radii of the LiH shells are

$$rs_{outer,j} := rs_j \cdot Ls$$

$$rsa_{outer,j} := rsa_j \cdot Ls$$

The assumed fraction of holes (out of 4π) (for driver beam access):

$$f_h := 0.05$$

$$f_h := 0.05$$

The corresponding shell masses are:

$$Mt_j := \frac{4}{3} \cdot (1 - f_h) \cdot \pi \cdot [(rs_j)^3 - ro^3] \cdot Ls^3 \cdot mds \quad \text{"Conventional" targets}$$

$$Mta_j := \frac{4}{3} \cdot (1 - f_h) \cdot \pi \cdot [(rsa_j)^3 - ro^3] \cdot Ls^3 \cdot mds \quad \text{"Advanced" targets}$$

Fig. 5- Fraction of fusion target yield captured in the target blanket shell vs driver energy, for constant plasma temp conventional and advanced targets.

Fig. 6 - Target shell mass M_t (kg) and outer radius r_s (cm) vs driver energy for conventional and advanced targets:

The fraction of each fusion yield available for useful direct conversion F_{DC} is less than $F_c(rs)$, less due to holes for driver access, less due to plasma radiation losses to the fluid Flibe walls, and less due to the residual chamber plasma that is not transferred out of chamber into the plasma accumulation chamber. That is, the residual plasma which is left behind to condense and mix into the Flibe stream. These losses of plasma energy unavailable to direct conversion still end up as heat in the Flibe which is available to the steam thermal cycle.

The peak reactor cavity LiH plasma density :

$$nco(Tco) = 7.246 \cdot 10^{22} \cdot pco \cdot (Tco)^{-1} \cdot (1 + a(Tco, pco, 0))^{-1}, \quad nco(Tco) = 1.1 \cdot 10^{25} \quad (\text{atoms/m}^3)$$

The corresponding peak chamber LiH plasma mass density is

$$mdc = 0.121 \cdot pco \cdot m(0) \cdot (Tco \cdot (1 + a(Tco, pco, 0)))^{-1}, \quad mdc = 0.1 \quad (\text{kg/m}^3)$$

The reactor cavity minor radius corresponding to each yield value is determined by the chosen peak plasma pressure pco , (plasma density nco and mass density mdc):

$$rc_j = \left(1.33 \cdot \frac{Mt_j}{8.38 \cdot mdc} \right)^{0.333} \quad (\text{m}), \text{ for conventional targets,} \quad rca_j = \left(1.33 \cdot \frac{Mta_j}{8.38 \cdot mdc} \right)^{0.333} \quad (\text{m}), \text{ for advanced targets.}$$

Integrating the radial heat flux over the plasma-filled chamber $Sw \sim \sigma T_{eff}^4$ at $T_{eff} \sim 5000$ deg, the temperature at which the Rosseland mean-free path is a minimum in the plasma edge gradient, one can obtain an expression for the energy lost by radiation (from the plasma edge) to the liquid Flibe walls during a transfer time from the reactor chamber into the central plasma accumulation chamber, for a transfer hole area to reactor cavity cross sectional area ratio of $\pi \cdot rc^2 / A_{tr} = 20$:

$$tr_j = \frac{8.38}{21.5} \cdot \ln(prpc) \cdot 20 \cdot rc_j \cdot \left(\sqrt{2 \cdot Tco \cdot 8.26 \cdot mo^{-1}} \right)^{-1} \quad tra_j = \frac{8.38}{21.5} \cdot \ln(prpc) \cdot 20 \cdot rca_j \cdot \left(\sqrt{2 \cdot Tco \cdot 8.26 \cdot mo^{-1}} \right)^{-1} \quad (\text{sec})$$

$$Qr_j = 5.67 \cdot 10^{-8} \cdot 5000^4 \cdot \left[21.5 \cdot (rc_j)^2 \right] \cdot tr_j \quad Qra_j = 5.67 \cdot 10^{-8} \cdot 5000^4 \cdot \left[21.5 \cdot (rca_j)^2 \right] \cdot tra_j \quad (\text{joules})$$

Fractions of captured yield lost by radiation to walls during transfer is: $Fr_j := 10^{-6} \cdot Qr_j \cdot [Y(E_d) \cdot Fs_j \cdot (1 - f_h)]^{-1}$ $Fra_j := 10^{-6} \cdot Qra_j \cdot [Ya(E_d) \cdot Fsa_j \cdot (1 - f_h)]^{-1}$

The fraction of target plasma left behind (assumed to condense on Flibe) is : $Fcon := prpc^{-1}$

The overall fractions of target fusion yield useful for direct conversion are then:

$$F_{DC_j} := Fs_j \cdot (1 - f_h) \cdot (1 - Fr_j) \cdot (1 - Fcon) \quad \text{and} \quad Fa_{DC_j} := Fsa_j \cdot (1 - f_h) \cdot (1 - Fra_j) \cdot (1 - Fcon)$$

Finally, the combined-cycle efficiencies are :

$$\eta_{cc_j} := [F_{DC_j} \cdot \eta_{DC} + (M - F_{DC_j}) \cdot \eta_{spp} + (1 - \eta_{DC}) \cdot F_{DC_j} \cdot \eta_{spp}] \cdot M^{-1} \quad \text{"Conventional" targets}$$

$$\eta^a_{cc_j} := [Fa_{DC_j} \cdot \eta_{DC} + (M - Fa_{DC_j}) \cdot \eta_{spp} + (1 - \eta_{DC}) \cdot Fa_{DC_j} \cdot \eta_{spp}] \cdot M^{-1} \quad \text{"Advanced" targets}$$

Fig. 7 Capture fraction useful for direct conversion F_{DC} , conventional and advanced targets, versus E_d :

Fig. 8 Combined cycle efficiency η_{cc} , conventional and advanced targets, and steam cycle efficiency versus E_d :

VI. SOLVING REP RATE AND POWER FLOWS PER UNIT FOR GIVEN NET ELECTRIC POWER/UNIT:

The following recirculating power flows reflect the HYLIFE-II power flow diagram of ref. 2, Fig. 5, with the following updated recirculating power terms (in MWe per fusion chamber unit) :

$$\text{Bypass pump power: } P_{bpp}(RR) := [(6.833 + 0.7938 \cdot RR + 0.2290 \cdot RR^2) \cdot \Phi(15 - RR) + 70.265 \cdot \Phi(RR - 15.001)] \cdot \eta_p^{-1}$$

The Heaviside step functions Φ force an upper limit to P_{bpp} equal to its value (87.8 MWe) at $RR=15$, whenever RR exceeds 15. This keeps the power balance solver from hanging up for matrix cases with very high RR . Thus P_{bpp} will be correct only when $RR < 15$. However, CoE will always minimize at $RR(\text{per unit}) < 15$ Hz anyway.

For $\Delta H_{tot} = 45$ m, the

$$\text{FVD+SG loop pump pwr: } P_{loop}(Pt) := 0.0686 \cdot \frac{Pt}{1000} \cdot 1.15 \cdot \Delta H_{tot} \cdot \eta_p^{-1}$$

Plant auxiliary power/unit: $P_{aux}(Pt) := f_{aux} \cdot Pt$

Power to the driver/unit: $P_{HI}(Ed, RR) := Ed \cdot RR \cdot \eta_{HI}(Ed)^{-1}$

Recirculating power/unit: $P_{rec}(Pt, Ed, RR) = P_{bpp}(RR) + P_{loop}(Pt) + P_{aux}(Pt) + P_{HI}(Ed, RR)$

CASE A - Conventional target gains and conventional steam cycle BoP:

Rep Rate/unit: $RR(Pt, Ed) := Pt \cdot (Ed \cdot (G(Ed) \cdot M + 1))^{-1}$

Initialize Pt for the solver: $P_t := 1.000$

Given

$$P_t = (P_e + P_{rec}(P_t, Ed, RR(P_t, Ed))) \cdot \eta^{-1}$$

$P_{th}(P_e, Ed, \eta) := \text{Find}(P_t)$ < This is the MathCAD solver

Thermal powers per fusion chamber:

Rep Rate per fusion chamber (Hz)

$$Pt_{j,k} := P_{th}(P_{eu,k}, Ed_j, \eta_{spp})$$

$$RRch_{j,k} := RR(Pt_{j,k}, Ed_j)$$

Recirculating power fraction:

Driver power per unit (MWe):

$$frec_{j,k} := \frac{P_{rec}(Pt_{j,k}, Ed_j, RRch_{j,k})}{Pt_{j,k} \cdot \eta_{spp}}$$

$$PHI_{j,k} := P_{HI}(Ed_j, RRch_{j,k})$$

Bypass pump power/unit:

$$Pb_{pp,j,k} := P_{bpp}(RRch_{j,k})$$

Fig. 9 Chamber rep rate [solid line (a)], recirculating power fraction [dashed line (a)], HI driver power [solid line (b)], and bypass pump power [dashed line (b)], as functions of driver energy, for 1000 MWe unit, conventional gains and steam BoP.

CASE B - Advanced target gains and conventional steam BoP:

$$\text{Rep Rate/unit: } \text{RRa}(\text{Pt}, \text{Ed}) := \text{Pt} \cdot (\text{Ed} \cdot (\text{Ga}(\text{Ed}) \cdot \text{M} + 1))^{-1}$$

Given

$$\text{P}_t := (\text{Pe} + \text{P}_{\text{rec}}(\text{P}_t, \text{Ed}, \text{RRa}(\text{P}_t, \text{Ed}))) \cdot \eta^{-1}$$

$$\text{Pa}_{\text{th}}(\text{Pe}, \text{Ed}, \eta) := \text{Find}(\text{P}_t)$$

Thermal powers per fusion chamber:

$$\text{Pt}_{a,j,k} := \text{Pa}_{\text{th}}(\text{Peu}_k, \text{Ed}_j, \eta_{\text{spp}})$$

Recirculating power fraction:

$$\text{frec}_{a,j,k} := \frac{\text{P}_{\text{rec}}(\text{Pt}_{a,j,k}, \text{Ed}_j, \text{RRch}_{a,j,k})}{\text{Pt}_{a,j,k} \cdot \eta_{\text{spp}}}$$

Bypass pump power/unit:

$$\text{Pb}_{\text{pp}}_{a,j,k} := \text{P}_{\text{bpp}}(\text{RRch}_{a,j,k})$$

Rep Rate per fusion chamber (Hz)

$$\text{RRch}_{a,j,k} := \text{RRa}(\text{Pt}_{a,j,k}, \text{Ed}_j)$$

Driver power per unit (MWe):

$$\text{PHI}_{a,j,k} := \text{P}_{\text{HI}}(\text{Ed}_j, \text{RRch}_{a,j,k})$$

CASE C - Conventional target gains and combined-cycle MHD+ steam BoP:

Thermal powers per fusion chamber:

$$\text{Pt}_{dc,j,k} := \text{P}_{\text{th}}(\text{Peu}_k, \text{Ed}_j, \eta_{\text{cc},j})$$

Recirculating power fraction:

$$\text{frec}_{dc,j,k} := \frac{\text{P}_{\text{rec}}(\text{Pt}_{dc,j,k}, \text{Ed}_j, \text{RRch}_{dc,j,k})}{\text{Pt}_{dc,j,k} \cdot \eta_{\text{cc},j}}$$

Rep Rate per fusion chamber (Hz)

$$\text{RRch}_{dc,j,k} := \text{RR}(\text{Pt}_{dc,j,k}, \text{Ed}_j)$$

Driver power per unit (MWe):

$$\text{PHI}_{dc,j,k} := \text{P}_{\text{HI}}(\text{Ed}_j, \text{RRch}_{dc,j,k})$$

Bypass pump power/unit:

$$\text{Pb}_{\text{pp}}_{dc,j,k} := \text{P}_{\text{bpp}}(\text{RRch}_{dc,j,k})$$

CASE D - Both advanced target gains and combined-cycle MHD+ steam BoP:

Thermal powers per fusion chamber:

$$\text{Pt}_{dca,j,k} := \text{Pa}_{\text{th}}(\text{Peu}_k, \text{Ed}_j, \eta_{a\text{cc},j})$$

Recirculating power fraction:

$$\text{frec}_{dca,j,k} := \frac{\text{P}_{\text{rec}}(\text{Pt}_{dca,j,k}, \text{Ed}_j, \text{RRch}_{dca,j,k})}{\text{Pt}_{dca,j,k} \cdot \eta_{a\text{cc},j}}$$

Rep Rate per fusion chamber (Hz)

$$\text{RRch}_{dca,j,k} := \text{RRa}(\text{Pt}_{dca,j,k}, \text{Ed}_j)$$

Driver power per unit (MWe):

$$\text{PHI}_{dca,j,k} := \text{P}_{\text{HI}}(\text{Ed}_j, \text{RRch}_{dca,j,k})$$

Bypass pump power/unit:

$$\text{Pb}_{\text{pp}}_{dca,j,k} := \text{P}_{\text{bpp}}(\text{RRch}_{dca,j,k})$$

Fig. 10 (a) RR vs Ed for conv. gains and BoP (solid), advanced gains and steam BoP (dashed), conv. gain and advanced BoP (dotted), and advanced gains and BoP (dash-dot). (b) HI driver power vs Ed for conv. gain and BoP (solid), advanced gain + steam BoP (dashed), and bypass pump power vs Ed for conv. (dotted) and advanced (dash-dot) gains with steam BoP. 1000 MWe units.

The following power flows are the disaggregated thermal powers delivered to the MHD generators and to the steam bottoming cycle for cases C and D with a combined cycle MHD + steam BoP. These power flows will be needed later on to cost the MHD generator and the steam cycle portions of the BoP separately.

Chamber plasma thermal power available to direct conversion: (Per-unit; for total plant, multiply by Nu)

Case C - Conventional target gains

$$Pt_{dcde_{j,k}} = Ed_j \cdot (G(Ed_j) + 1) \cdot RRch_{dc_{j,k}} \cdot F_{DC_j}$$

CASE D - Advanced target gains

$$Pt_{dcdca_{j,k}} = Ed_j \cdot (Ga(Ed_j) + 1) \cdot RRch_{dca_{j,k}} \cdot Fa_{DC_j}$$

Thermal power available to the steam bottoming cycle with direct conversion:

Case C - Conventional target gains

$$Pt_{dcs_{j,k}} = Ed_j \cdot (G(Ed_j) \cdot M + 1) \cdot RRch_{dc_{j,k}} \cdot \left[1 - \frac{F_{DC_j}}{M} + (1 - \eta_{DC}) \cdot \frac{F_{DC_j}}{M} \right]$$

CASE D - Advanced target gains

$$Pt_{dcsa_{j,k}} = Ed_j \cdot (Ga(Ed_j) \cdot M + 1) \cdot RRch_{dca_{j,k}} \cdot \left[1 - \frac{Fa_{DC_j}}{M} + (1 - \eta_{DC}) \cdot \frac{Fa_{DC_j}}{M} \right]$$

Fig. 11- Thermal power flows vs Ed with combined cycle MHD+steam BoP (DC) for (a) conventional target gains, and for (b) advanced target gains. Total thermal for Case A and C (steam BoP, no DC) - (solid lines), thermal to steam bottom cycle (dotted lines) and thermal to MHD direct converters (dashed lines). All cases for one 1000 MWe unit.

For some subsystem costing needing gross electric power flows, multiply the thermal powers by the appropriate efficiency: η_{spp} for cases A and B, η_{cc} and η_{acc} for total gross electric for cases C and D, respectively. For the portion of gross electric from MHD generators in cases D and C, multiply the associated Pt_{dcdc} and Pt_{dcdca} by η_{DC} , and for the portion from the steam bottom cycle, multiply the Pt_{dcs} and Pt_{dcsa} by η_{spp} .

Fig.12 - Plant efficiencies vs E_d , with conventional target gains and steam BoP (solid line), advanced target gains and conventional steam BoP (dashed line), conventional target gains and advanced MHD +steam BoP (dotted line), and advanced target gains and advanced BoP (dash-dot line). All cases for 1000 MWe units.

VII. DIRECT CAPITAL COSTS

All costs are in millions of constant 93 \$. Costs of subsystems developed in 1990 \$ (eg., those derived from Delene's 1990 paper) will be escalated by a factor of 1.06 to 1993\$. Cost accounts 20 through 27 are all addressed in what follows, not in sequence, but grouped according to the three categories that people usually think about as three main groups that make up an IFE power plant: Driver (DR), Fusion Chamber (FC), and Steam Power Plant (SP). For future cases that would include an MHD direct conversion topping cycle, there will be a few specific new subsystems added to the fusion chamber group, with most of the MHD converter equipment added to the steam plant. The buildings (Account 21-Structures and Improvements), for example, are disaggregated into the three categories. After CoE is optimized later on, all traditional cost accounts for reference cases will be put back into the usual form for comparison with other studies, with the same total as obtained by adding the costs of the three categories. The driver is assumed to be sufficiently modular with spares, or sufficiently reliable, that one driver is optimum for driving all fusion chamber units in a plant. Costs of a beam switch yard, the driver, the target injector, and the driver building are included in the "Driver" category. Costs in the "Fusion Chamber" category include the fusion chambers, target factory, remote maintenance, Flibe blankets, heat transport system and steam generators, Flibe vacuum disengagers, tritium fuel management system, and the fusion chamber building (one for each fusion chamber unit is assumed for maintenance reasons). Everything else is included in the "SP" category. Fusion chamber and conventional steam conversion systems costs and scaling with the economy-of-scale associated with the size of a single unit or system are based on the HYLIFE-II study^{(2),(3)}, escalated to 1993\$, and updated where appropriate. Where multiple systems or units are used, the direct costs are modified by Delene's adjustment factors $cd(Nu)$ for multiple units. Cases with more than one steam plant per fusion chamber unit have an additional reduction (1-savings) applied to the SP costs. Gain curves from Fig.2 are assumed, and Woodworth's target fab costs for indirect drive targets are assumed, plus additional target fab costs when target blanket shells are used for direct conversion.

DRIVER-GROUP

Driver Equipment - one driver assumed per plant, with a switchyard to drive multiple units.
(All costs in 1993 \$, with subsystem costs that had been in 1990 \$ escalated by 1.06 to 1993 \$)

27 Heavy-Ion Driver

Based on Improved 3-Ring Recirculator Model (Bieri's published article in Proceedings of the 1993 Particle Accelerator Conference, Washington D.C. May, 1993. This work is the latest, was not available for the last HYLIFE-II publication. It is still not fully optimized, since it was based on the LLNL "C" recirculator ("black book") design, but it did correct a major deficiency: it put in explicit economy-of-scale for each individual driver subsystem, so that driver cost versus E_d would be better represented. This version, in consultation with Bieri and Newton after the above reference was submitted, went even further to include driver cost scaling with rep-rate at a fixed E_d , to account for driver power and cooling costs.

27.1 Heavy ion accelerator

$$C_{HIB}(Ed, RR, Nu) = \frac{363}{1.125} \cdot 1.06 \cdot \left(\frac{Ed}{4}\right)^{0.4} + \frac{63}{1.125} \cdot 1.06 \cdot \left(\frac{Nu \cdot RR \cdot Ed \cdot 0.35}{20 \cdot \eta_{HI}(Ed)}\right)^{0.67}$$

<Note that RP in C_{HIB} is per unit; RR is multiplied in the second term by Nu.

The first term on the RHS reflects a modest economy-of-scale with driver energy per pulse. The second term reflects the dependence of cost on average power (Nu and RR dependent) expected for efficient accelerators (the cooling system, and the front-end AC and DC power supplies). For those cases assuming advanced targets (based on the "Fast-Ignitor"), the driver costs will be C_{HIB} which for the main HIB driver used for fuel compression, plus a fixed direct cost for a DPSSL ignitor beam of

$$C_{FIB} = 50 \quad (\text{Taken as 1993 \$})$$

27.2 Beam switchyard

$$C_{BSY}(Nu) = \frac{24}{1.125} \cdot 1.06 \cdot cd(Nu)$$

This reflects the cost of a beam switch yard and final focus systems and its dependence on the number of fusion chamber units serviced by the switchyard. Here, we assume heavy ion targets capable of single-sided illumination (to minimize the number of beam steering magnets required), so that the switchyard and final focus total capital cost per unit is only $24 \cdot 1.963 \sim 50M\$/unit$, rather than $100M\$/unit$ total cost per unit. Nonetheless, we will study the sensitivity of varying the switchyard costs up to $100 M\$/unit$.

27.3 Target injector system

$$C_{INJ}(RR, Nu) = 4.8 \cdot 1.06 \cdot (RR \cdot 5^{-1})^{0.7} \cdot cd(Nu)$$

21.5 Heavy-Ion Driver Building:

$$C_{DRB}(Ed) = \frac{31.5}{1.125} \cdot 1.06 \cdot (Ed \cdot 4^{-1})^{0.5}$$

Direct costs for the driver group with conventional targets (Cases A and C) :

$$C_{DRG}(Ed, RR, Nu) = C_{HIB}(Ed, RR, Nu) + C_{BSY}(Nu) + C_{INJ}(RR, Nu) + C_{DRB}(Ed)$$

Direct costs for the driver group with advanced targets (Cases B and D):

$$C_{aDRG}(Ed, RRa, Nu) = C_{HIB}(Ed, RRa, Nu) + C_{BSY}(Nu) + C_{INJ}(RRa, Nu) + C_{DRB}(Ed) + C_{FIB}$$

Fig. 13 -This plot of the heavy-ion driver group direct capital cost (in 1993 M\$) vs E_d shows the effect of the third and second term in C_{HIB} (with dependence on Nu and RR) exhibiting a minimum in driver cost vs E_d , and raising the cost to drive four high power (1000 MWe) units -dashed curve, compared to two-2000 MWe units-solid curve. The dash-dot line curve for one 2000 MWe unit, and the dotted line for one unit at 250 MWe shows how lower rep rates and driver powers with advanced targets reduce cost at low driver energy. (shifts minima to the left). All curves turn eventually turn up at sufficiently low E_d , because RR increases to keep P_{net} constant. The driver energies which minimize overall CoE are not generally at the driver cost minima for these example plants (generally, CoE minimizes to the right of the driver cost minima because of bypass pumping and target fab costs, as will be shown in later sections.

FUSION CHAMBER GROUP

(Formerly, "Reactor-Plant Equipment, but here includes the associated structures.
Direct capital costs in millions of FY93 dollars)

21.2 Fusion Chamber Buildings-for Nu chambers, cost scaled with chamber thermal power, to properly credit reduced thermal power to steam (into the Flibe in the chamber) P_{tDCSR} when a combined cycle is used .

$$C_{FCB}(Nu, Pt, \eta) = 30.9 \cdot 1.06 \cdot (Pt \cdot \eta \cdot 1100^{-1}) \cdot cd(Nu)$$

Direct cost for Nu fusion chamber buildings,
with Delene factor. Assumed non-nuclear grade.

22.1 Fusion Chamber: Vessel, Bypass Pumps, and Bypass Pipes- there are Nu- fusion chamber units per plant.

Thermal power delivered to the Flibe within the fusion chambers is just Pt and Pta with conventional BoP in Cases A and B. When direct conversion is used, costs scale with the following partial thermal powers delivered to the Flibe in the chambers

$$Pt_{dcsr_{j,k}} = Y(E_{d_j}) \cdot RRch_{dc_{j,k}} \cdot (M - F_{DC_j}) \quad (\text{use for case C})$$

$$Pt_{dcsra_{j,k}} = Ya(E_{d_j}) \cdot RRch_{dca_{j,k}} \cdot (M - Fa_{DC_j}) \quad (\text{use for case D})$$

22.1.1 Fusion Chamber

$$C_{FC}(Nu, Pt, Y) := 14.4 \cdot 1.06 \cdot \left[(Pt \cdot 2500^{-1})^{0.855} + \frac{Y}{350} \right] \cdot cd(Nu)$$

Total direct cost for Nu units, with Delene factor. No CF_{NS} factor is used to credit non-nuclear grade. Yield dependent term corresponds to 300 tons steel per 4000 MJ yield virial coefficient. (CFARII value ~3x Russian) This gives same cost for HYLIFEII @ 350 MJ, but doubles the chamber cost at 1 GJ yield, for the same thermal power.

22.1.2 Bypass Pumps

$$C_{BPP}(RR, Nu) := 55.1 \cdot 1.06 \cdot \left(\frac{P_{bpp}(RR)}{24.8} \right)^{1.0} \cdot cd(Nu)$$

22.1.3 Bypass Pipes

$$C_{BPPipes}(Nu, Pt) := 9.2 \cdot 1.06 \cdot \left(\frac{Pt}{2500} \right)^{0.69} \cdot cd(Nu)$$

The Number of Total Steam Power Plants N_{spp} and Coolant Loops N_{loop} for an Nu-chamber multi-unit plant:

$$\text{No. of steam power plants (SPP) per unit: } N_{spp}(Pt) := \text{ceil} \left(Pt \cdot \eta_{spp} \cdot 1300^{-1} \right) \quad \text{where } \eta_{spp} = 0.43$$

$$\text{No. of steam generator (SG) loops per unit: } N_{loops}(Pt) := N_{spp}(Pt) \cdot \text{ceil} \left(Pt \cdot 1000^{-1} \cdot N_{spp}(Pt)^{-1} \right)$$

$$\text{For example, for thermal power per unit } Pt = 2700 \text{ MW}_{th}, \quad N_{spp}(2700) = 1 \quad N_{loops}(2700) = 3$$

$$\text{and for } Pt = 5100 \text{ MW}_{th}, \quad N_{spp}(5100) = 2 \quad N_{loops}(5100) = 6$$

The Volume of Flibe Coolant

$$V_{Flibe}(RR, Nu, Pt) := \left[1202 - 5.662 \cdot RR + 3.714 \cdot RR^2 + 690 \cdot \left(\frac{N_{loops}(Pt)}{3} - 1 \right) \right]$$

$$\text{22.2 Flibe Coolant} \quad \rho_{Flibe} = 1970 \quad (\text{kg/m}^3)$$

$$C_{Flibe}(RR, Nu, Pt) := 42 \cdot 10^{-6} \cdot 1.06 \cdot \left(\frac{1.22}{1.936} \right) \cdot \rho_{Flibe} \cdot V_{Flibe}(RR, Nu, Pt) \cdot cd(Nu)$$

This Flibe cost is not the actual direct cost, but reduced by 1.22/1.936, so that when later multiplied by the 1.936 indirect cost factor, the total cost will be only 22% greater than the direct cost, which allows only for the usual contingency included in the indirect costs. This is because Flibe is a commodity in amounts unusual for typical nuclear plants, from which the 1.936 IDC was based.

22.3 Vacuum System (in Account 22.5)

22.4 –Target Factory and Tracking equipment (as per Woodworth) : One target factory per plant; no Delene factor

$$C_{TFE}(RR, Nu, Pt, \eta) := 31.3 \cdot 1.06 \cdot \left[0.14 + 0.73 \cdot \left(\frac{RR \cdot Nu}{5} \right)^{0.7} + 0.13 \cdot \left(\frac{Nu \cdot Pt \cdot \eta}{1000} \right)^{0.67} \right] \cdot CF_{NS}$$

21.6 Target factory building:

$$C_{TFB}(RR, Nu) := 13.3 \cdot 1.06 \cdot \left(\frac{RR \cdot Nu}{5} \right)^{0.3}$$

For advanced cases with direct conversion using target blanket shells (Cases C and D) there is in addition:

Target shell cap. equipment: $C_{TSE}(RR, Nu, Mt) := 16.7 \cdot (Nu \cdot RR \cdot Mt \cdot 10^{-1})^{0.7} \cdot CF_{NS}$ based on 15 kcal/mole net extraction, 1\$/ W process cost.

Target blanket shell building (extension of target fab bldg): $C_{TSB}(RR, Nu, Mt) := 0.33 \cdot C_{TFB}(RR, Nu)$

The target blanket shell lithium extraction will consume additional auxiliary electric power- this is for info only; the direct conversion efficiency of 52 %, down from 55% already includes this loss in the extraction of working material.

$$P_{TBS}(RR, Mt) := 75 \cdot RR \cdot Mt \cdot prpc^{-1} \quad (MWe)$$

Based on 15 kcal/mole extraction energy for lithium from Flibe.

Annual target fab operating costs are much higher than 3% of the target factory capital (Bernat, Woodworth):

$$OM_{TF}(RR, Nu) := 12 \cdot (Nu \cdot RR \cdot 5^{-1})^{0.3} \quad (M \text{ 1993 } \$ / yr)$$

Target costs / yr, without target shells (no Direct Conversion) : Total costs, direct * indirect multiplier.

$$TCPY(RR, Nu, Pt, \eta) := 0.0966 \cdot IDC \cdot (C_{TFE}(RR, Nu, Pt, \eta) + C_{TFB}(RR, Nu)) + OM_{TF}(RR, Nu)$$

With Direct Conversion:

$$TCPY_{dc}(RR, Nu, Pt, \eta, Mt) := 0.0966 \cdot IDC \cdot (C_{TFE}(RR, Nu, Pt, \eta) + C_{TFB}(RR, Nu) + C_{TSE}(RR, Nu, Mt) + C_{TSB}(RR, Nu, Mt) + 1.5 \cdot OM_{TF}(RR, Nu))$$

The No. of targets produced per year : $NTPY(RR, Nu, Fa) := 3 \cdot 10^7 \cdot Nu \cdot RR \cdot Fa$

Fig. 14 - Cost per target (in cents per target, based on annual expenses, 1993\$) versus no. of 1000 MWe units. Ed = 5 MJ.

22.5 Tritium Management System

$$C_{TMS}(Nu, Pt) := (16.0 + 15.1 \cdot N_{loops}(Pt)) \cdot 1.06 \cdot CF_{NS} \cdot cd(Nu)$$

Total capital costs for Nu chamber units, with Delene factor, and nuclear-grade factor. Includes two-stage Flibe vacuum tritium disengagers.

22.6 Shielding-included with account 21 (buildings)

22.7 Heat Transport System (In all account 22.7 subsystems, use the thermal power available to the SPP- P_{tdcs} , or P_{tdcsa}

with advanced targets, when advanced BoP [MHD+steam combined cycle] is assumed)

22.7.1 Coolant Loop Piping Double-wall piping: $K_{DWP} := 0.018$ M\$ per meter, $L_{DWP} := 75$ (m)

Single-wall piping: $K_{SWP} := 0.0115$ M\$ per meter, $L_{SWP} := 140$ (m)

$$C_{DWP}(Nu, Pt) := K_{DWP} \cdot L_{DWP} \cdot CF_{NS} \cdot 1.06 \cdot N_{loops}(Pt) \cdot cd(Nu)$$

$$C_{SWP}(Nu, Pt) := K_{SWP} \cdot L_{SWP} \cdot 1.06 \cdot N_{loops}(Pt) \cdot cd(Nu)$$

$$C_{CLP}(Nu, Pt) := C_{DWP}(Nu, Pt) + C_{SWP}(Nu, Pt) \quad < \text{combines both double and single-wall piping}$$

22.7.2 Coolant Valves and Bellows

$$CF_{misc} := 1.05$$

$$C_{CVB}(Nu, Pt) := 6.05 \cdot 1.06 \cdot N_{loops}(Pt) \cdot CF_{misc} \cdot cd(Nu)$$

22.7.3 Coolant Pumps and Motors

$$\Delta T_{Fl} := 50$$

$$C_{CPM}(Nu, Pt) := 1.54 \cdot 1.06 \cdot \left(\frac{Pt}{\Delta T_{Fl} \cdot N_{loops}(Pt)} \right)^{0.74} \cdot N_{loops}(Pt) \cdot cd(Nu)$$

22.7.4 Coolant Cleanup Plant

$$C_{CCP}(Nu, Pt) := 0.30 \cdot 1.06 \cdot \left(\frac{Pt}{\Delta T_{Fl} \cdot N_{loops}(Pt)} \right) \cdot N_{loops}(Pt) \cdot cd(Nu)$$

22.7.5 Steam Separators

$$C_{SS}(Nu, Pt) := 13.8 \cdot 1.06 \cdot \left(\frac{Pt}{3800} \right) \cdot cd(Nu)$$

22.7.6 Water Loop Piping

$$C_{WLP}(Nu, Pt) := 0.19 \cdot 1.06 \cdot \left(\frac{Pt}{3800} \right)^{0.5} \cdot cd(Nu)$$

22.7.7 Steam Generators

$$C_{SG}(Nu, Pt) := 67.3 \cdot 1.06 \cdot \left(\frac{Pt}{2500 \cdot N_{spp}(Pt)} \right)^{0.4} \cdot N_{spp}(Pt) \cdot cd(Nu)$$

22.8 Remote Maintenance Equipment :

$$C_{RME}(Nu, Peu) := 40 \cdot 1.06 \cdot \left(\frac{Peu}{1000} \right)^{0.6} + 10 \cdot 1.06 \cdot \left(\frac{Peu}{1000} \right)^{0.6} \cdot cd(Nu) \quad \text{This allocates 80 \% of general-purpose remote maintenance equipment in common for all units, with 20\% replicated for each unit.}$$

22.9 Special-Direct Conversion Chamber Interface

This category applies only for cases when direct conversion of target shell plasma is assumed. Includes MHD generator exhaust heat-exchange to the Flibe loops, the adjacent plasma storage chambers for feeding the MHD generators between shots, and one-way magnetic "valves" for control of plasma flow between the pulsed chambers and the adjacent plasma storage chambers at lower plasma pressure.

$$C_{DCI}(Nu, Pt_{dcdc}) := 57 \cdot (Pt_{dcdc} \cdot 4000 \cdot 1)^{0.67} \cdot cd(Nu) \quad (1993 \$)$$

(Use Pt_{dcdc} , the plasma power available to direct conversion. Costs based on the CFAR study⁴).

Direct costs for the fusion chamber group (Cases A and B for conventional steam cycle):

[use RR_a , Pt_a for case B]

$$\begin{aligned} C_{FCG}(RR, Nu, Pt, Peu, Y) := & C_{FCB}(Nu, Pt, \eta_{spp}) + C_{FC}(Nu, Pt, Y) + C_{BPP}(RR, Nu) + C_{BPPipes}(Nu, Pt) \dots \\ & + C_{Flibe}(RR, Nu, Pt) + C_{TFE}(RR, Nu, Pt, \eta_{spp}) + C_{TFB}(RR, Nu) + C_{TMS}(Nu, Pt) \dots \\ & + C_{DWP}(Nu, Pt) + C_{SWP}(Nu, Pt) + C_{CVB}(Nu, Pt) + C_{CPM}(Nu, Pt) + C_{CCP}(Nu, Pt) \dots \\ & + C_{SS}(Nu, Pt) + C_{WLP}(Nu, Pt) + C_{SG}(Nu, Pt) + C_{RME}(Nu, Peu) \end{aligned}$$

STEAM POWER PLANT GROUP—this group includes all items not already covered in the driver and fusion chamber groups, including MHD generators and heat exhaust-exchange to Flibe in cases C and D.

20. Land and Land Rights $C_{LLR}(Nu) := 11 \cdot 1.06 \cdot cd(Nu)$

21 Site Improvement and Structures (Here, other than buildings for the driver and fusion chamber groups)

21.3 Steam Plant Buildings $C_{SPB}(Nu, Pt) := 71.7 \cdot 1.06 \cdot \left(\frac{Pt \cdot \eta_{spp}}{1100} \right)^{0.5} \cdot cd(Nu)$

(Use steam power Pt_{dcs} with MHD + steam cases C and D to credit smaller BoP)

21.7 Direct Conversion Building $C_{DCB}(Nu, Pt_{dcdc}) := 20 \cdot (Pt_{dcdc} \cdot 4000 \cdot 1)^{0.5} \cdot cd(Nu)$
(only for future Cases C and D)

(Based on CFAR II study⁴)

23. Turbine Plant and Direct Conversion Equipment

23.1 Turbine Plant Equipment For 2 SPP's per unit, there is a cost savings of $f_{\text{savings}}=12\%$. Limit to $N_{\text{spp}}=1$ or 2 only.

$$C_{\text{TPE}}(\text{Nu}, \text{Pt}) := 205 \cdot 1.06 \cdot \left(\frac{\text{Pt} \cdot \eta_{\text{spp}}}{1282 \cdot N_{\text{spp}}(\text{Pt})} \right)^{0.8} \cdot [1 - f_{\text{savings}} \cdot (N_{\text{spp}}(\text{Pt}) - 1)] \cdot N_{\text{spp}}(\text{Pt}) \cdot \text{cd}(\text{Nu})$$

(Use Pt_{dcs} , the portion of thermal power to the steam plant, when MHD+steam combined cycle is assumed in cases C&D).

23.2 Direct Conversion Equipment (for cases C and D) --- Here again, we assume one MHD generator per fusion chamber unit when MHD combined cycle is assumed. This DC equipment is then added to the 23.1 turbine plant equipment for the remaining power going into the steam bottoming cycle. We omit here DC to AC inversion, since hydrogen electrolysis would be cheaper by running directly off the DC, saving the cost of conversion from AC back to DC (direct current here) also. These savings in on the electrolysis power supply side will be credited for the DC power produced in the electrical plant (Acc. 24). The direct conversion costing here is based on MHD generator BoP costing developed in the CFAR II study⁴, which was 41 M\$ per GWe for Flibe, including the DC building, for one MHD generator, and no DC to AC. That design was for high pressure (200 atm) plasma sources, to reduce radiation losses for low-lithium-content, high molecular weight working fluids. For lithium hydride working fluids⁴ assumed here, the CFARII BoP cost per unit power was half that with Flibe, but to compensate for lower pressures and larger physical size (albeit at lower fields), this study uses the same 41 M\$ per GWe, with the same MHD economy-of-scale exponent of 0.67 for CFARII BoP.

$$C_{\text{DCE}}(\text{Nu}, \text{Pt}_{\text{dcdc}}) := 41 \cdot \left(\frac{\text{Pt}_{\text{dcdc}} \cdot \eta_{\text{DC}}}{1000} \right)^{0.67} \cdot \text{cd}(\text{Nu})$$

(Use Pt_{dcdc} , the plasma power to the MHD generators, when combined cycle is assumed for D & C cases).

24. Electrical Plant Equipment

$$C_{\text{EPE}}(\text{Nu}, \text{Pt}) := 65 \cdot 1.06 \cdot \left(\frac{\text{Pt} \cdot \eta_{\text{spp}}}{1282 \cdot N_{\text{spp}}(\text{Pt})} \right)^{0.4} \cdot [1 - f_{\text{savings}} \cdot (N_{\text{spp}}(\text{Pt}) - 1)] \cdot N_{\text{spp}}(\text{Pt}) \cdot \text{cd}(\text{Nu})$$

Since the MHD generator output voltage is convenient to run electrolysis cells directly, use Pt_{dcs} , the thermal power delivered to the steam turbine generators here, for combined cycles is cases C and D.

25. Miscellaneous Plant Equipment

$$C_{\text{MPE}}(\text{Nu}, \text{Pt}) := 25 \cdot 1.06 \cdot \left(\frac{\text{Pt} \cdot \eta_{\text{spp}}}{1282 \cdot N_{\text{spp}}(\text{Pt})} \right)^{0.3} \cdot [1 - f_{\text{savings}} \cdot (N_{\text{spp}}(\text{Pt}) - 1)] \cdot N_{\text{spp}}(\text{Pt}) \cdot \text{cd}(\text{Nu})$$

(Use Pt_{dcs} , the thermal power delivered to the steam plant, for cases C and D).

26. Heat Rejection Equipment The heat rejected per SPP is given by $Q_{\text{reject}}(\text{Pt}) := (1 - \eta_{\text{spp}}) \cdot \text{Pt} \cdot N_{\text{spp}}(\text{Pt})^{(-1)}$

(Use Pt_{dcs} , the thermal power to the steam, for cases C and D with MHD combined cycle).

$$C_{\text{MHRS}}(\text{Nu}, \text{Pt}) := 42 \cdot 1.06 \cdot \left(\frac{Q_{\text{reject}}(\text{Pt})}{1719} \right)^{0.8} \cdot [1 - f_{\text{savings}} \cdot (N_{\text{spp}}(\text{Pt}) - 1)] \cdot N_{\text{spp}}(\text{Pt}) \cdot \text{cd}(\text{Nu})$$

Steam power plant group costs: $C_{\text{SPG}}(\text{Nu}, \text{Pt}) := C_{\text{LLR}}(\text{Nu}) + C_{\text{SPB}}(\text{Nu}, \text{Pt}) + C_{\text{TPE}}(\text{Nu}, \text{Pt}) + C_{\text{EPE}}(\text{Nu}, \text{Pt}) \dots$
 $+ C_{\text{MPE}}(\text{Nu}, \text{Pt}) + C_{\text{MHRS}}(\text{Nu}, \text{Pt})$

Direct costs for the fusion chamber group, with MHD+steam combined cycle (cases C and D):

$$Cdc_{FCG}(RR, Nu, Pt_{dc}, Pt_{dcs}, Pt_{dcdc}, Pt_{dcsr}, Peu, Y, Mt, \eta) = C_{FCB}(Nu, Pt_{dcsr}, \eta_{spp}) + C_{FC}(Nu, Pt_{dcsr}, Y) + C_{Bpp}(RR, Nu) \\ + C_{BppPipes}(Nu, Pt_{dcsr}) + C_{Flibe}(RR, Nu, Pt_{dcs}) \dots \\ + C_{TFE}(RR, Nu, Pt_{dc}, \eta) + C_{TSE}(RR, Nu, Mt) \dots \\ + C_{TFB}(RR, Nu) + C_{TSB}(RR, Nu, Mt) + C_{TMS}(Nu, Pt_{dcs}) \\ + C_{CLP}(Nu, Pt_{dcs}) + C_{CVB}(Nu, Pt_{dcs}) + C_{CPM}(Nu, Pt_{dcs}) \dots \\ + C_{CCP}(Nu, Pt_{dcs}) + C_{SS}(Nu, Pt_{dcs}) + C_{WLP}(Nu, Pt_{dcs}) \dots \\ + C_{SG}(Nu, Pt_{dcs}) + C_{RME}(Nu, Peu) + C_{DCI}(Nu, Pt_{dcdc})$$

[for case D with advanced target gains, use RR's, η_{cc} 's, Mt's, Y's, and Pt's with added subscript "a" as defined above]

Direct costs for the steam plant group, with MHD+steam combined cycle (cases C and D):

$$Cdc_{SPG}(Nu, Pt_{dcs}, Pt_{dcdc}) = C_{LLR}(Nu) + C_{SPB}(Nu, Pt_{dcs}) + C_{DCB}(Nu, Pt_{dcdc}) \dots \\ + C_{TPE}(Nu, Pt_{dcs}) + C_{DCE}(Nu, Pt_{dcdc}) \dots \\ + C_{EPE}(Nu, Pt_{dcs}) + C_{MPE}(Nu, Pt_{dcs}) + C_{MHRs}(Nu, Pt_{dcs})$$

28. Hydrogen Electrolysis Plant— this section will be completed after the minimum CoE benchmark cases are completed. This section will later add the electrolysis plant capital cost/kWe to be used in the subsequent calculation of minimum Cost of Hydrogen (CoH) in \$/GJ. The electrolysis plant capital cost is a function of the electrolysis efficiency, since the cell voltage runs higher than the minimum thermodynamic value as the cell plate current density increases. Thus, the cell size and cost/kWe increases with decreasing current density (increasing cell efficiency). This is the classic economic trade-off for electrolysis, where the optimum depends both on the cell cost vs size, and the cost of electricity. Adding the electrolysis plant capital cost may shift the optimum driver rep-rate and energy for minimum CoH.

CALCULATE CAPITAL COSTS FOR FOUR CASES, for each heavy-ion driver energy, unit size, and number of units:

Group cost labels are in the form [case letter][group designate][Nu] . "j,k" are indicis for each driver energy and net power/unit.

CASE (A) - CONVENTIONAL TARGET GAINS WITH CONVENTIONAL STEAM BOP

$$\begin{aligned} Adr1_{j,k} &= C_{DRG}(Ed_j, RRch_{j,k}, 1) & Adr2_{j,k} &= C_{DRG}(Ed_j, RRch_{j,k}, 2) \\ Adr4_{j,k} &= C_{DRG}(Ed_j, RRch_{j,k}, 4) & Adr8_{j,k} &= C_{DRG}(Ed_j, RRch_{j,k}, 8) \\ Afc1_{j,k} &= C_{FCG}(RRch_{j,k}, 1, Pt_{j,k}, Peu_k, Y(Ed_j)) & Afc2_{j,k} &= C_{FCG}(RRch_{j,k}, 2, Pt_{j,k}, Peu_k, Y(Ed_j)) \\ Afc4_{j,k} &= C_{FCG}(RRch_{j,k}, 4, Pt_{j,k}, Peu_k, Y(Ed_j)) & Afc8_{j,k} &= C_{FCG}(RRch_{j,k}, 8, Pt_{j,k}, Peu_k, Y(Ed_j)) \\ Asp1_{j,k} &= C_{SPG}(1, Pt_{j,k}) & Asp2_{j,k} &= C_{SPG}(2, Pt_{j,k}) \\ Asp4_{j,k} &= C_{SPG}(4, Pt_{j,k}) & Asp8_{j,k} &= C_{SPG}(8, Pt_{j,k}) \end{aligned}$$

CASE (B) - ADVANCED TARGET GAINS WITH CONVENTIONAL STEAM BOP

$$\begin{aligned} Bdr1_{j,k} &= Ca_{DRG}(Ed_j, RRch_{a_{j,k}}, 1) & Bdr2_{j,k} &= Ca_{DRG}(Ed_j, RRch_{a_{j,k}}, 2) \\ Bdr4_{j,k} &= Ca_{DRG}(Ed_j, RRch_{a_{j,k}}, 4) & Bdr8_{j,k} &= Ca_{DRG}(Ed_j, RRch_{a_{j,k}}, 8) \\ Bfc1_{j,k} &= C_{FCG}(RRch_{a_{j,k}}, 1, Pt_{a_{j,k}}, Peu_k, Ya(Ed_j)) & Bfc2_{j,k} &= C_{FCG}(RRch_{a_{j,k}}, 2, Pt_{a_{j,k}}, Peu_k, Ya(Ed_j)) \\ Bfc4_{j,k} &= C_{FCG}(RRch_{a_{j,k}}, 4, Pt_{a_{j,k}}, Peu_k, Ya(Ed_j)) & Bfc8_{j,k} &= C_{FCG}(RRch_{a_{j,k}}, 8, Pt_{a_{j,k}}, Peu_k, Ya(Ed_j)) \\ Bsp1_{j,k} &= C_{SPG}(1, Pt_{a_{j,k}}) & Bsp2_{j,k} &= C_{SPG}(2, Pt_{a_{j,k}}) \\ Bsp4_{j,k} &= C_{SPG}(4, Pt_{a_{j,k}}) & Bsp8_{j,k} &= C_{SPG}(8, Pt_{a_{j,k}}) \end{aligned}$$

CASE (C) - CONVENTIONAL TARGET GAINS WITH MHD+STEAM COMBINED CYCLE BOP

$$\begin{aligned}
 Cdr1_{j,k} &= C_{DRG}(Ed_j, RRch_{dc,j,k}, 1) & Cdr2_{j,k} &= C_{DRG}(Ed_j, RRch_{dc,j,k}, 2) \\
 Cdr4_{j,k} &= C_{DRG}(Ed_j, RRch_{dc,j,k}, 4) & Cdr8_{j,k} &= C_{DRG}(Ed_j, RRch_{dc,j,k}, 8) \\
 Cfc1_{j,k} &= Cdc_{FCG}(RRch_{dc,j,k}, 1, Pt_{dc,j,k}, Pt_{dcs,j,k}, Pt_{dcdc,j,k}, Pt_{dcsr,j,k}, Peu_k, Y(E_d_j), Mt_j, \eta_{cc_j}) \\
 Cfc2_{j,k} &= Cdc_{FCG}(RRch_{dc,j,k}, 2, Pt_{dc,j,k}, Pt_{dcs,j,k}, Pt_{dcdc,j,k}, Pt_{dcsr,j,k}, Peu_k, Y(E_d_j), Mt_j, \eta_{cc_j}) \\
 Cfc4_{j,k} &= Cdc_{FCG}(RRch_{dc,j,k}, 4, Pt_{dc,j,k}, Pt_{dcs,j,k}, Pt_{dcdc,j,k}, Pt_{dcsr,j,k}, Peu_k, Y(E_d_j), Mt_j, \eta_{cc_j}) \\
 Cfc8_{j,k} &= Cdc_{FCG}(RRch_{dc,j,k}, 8, Pt_{dc,j,k}, Pt_{dcs,j,k}, Pt_{dcdc,j,k}, Pt_{dcsr,j,k}, Peu_k, Y(E_d_j), Mt_j, \eta_{cc_j}) \\
 Csp1_{j,k} &= Cdc_{SPG}(1, Pt_{dcs,j,k}, Pt_{dcdc,j,k}) & Csp4_{j,k} &= Cdc_{SPG}(4, Pt_{dcs,j,k}, Pt_{dcdc,j,k}) \\
 Csp2_{j,k} &= Cdc_{SPG}(2, Pt_{dcs,j,k}, Pt_{dcdc,j,k}) & Csp8_{j,k} &= Cdc_{SPG}(8, Pt_{dcs,j,k}, Pt_{dcdc,j,k})
 \end{aligned}$$

CASE (D) - ADVANCED TARGET GAINS WITH MHD+STEAM COMBINED CYCLE BOP

$$\begin{aligned}
 Ddr1_{j,k} &= Ca_{DRG}(Ed_j, RRch_{dca,j,k}, 1) & Ddr2_{j,k} &= Ca_{DRG}(Ed_j, RRch_{dca,j,k}, 2) \\
 Ddr4_{j,k} &= Ca_{DRG}(Ed_j, RRch_{dca,j,k}, 4) & Ddr8_{j,k} &= Ca_{DRG}(Ed_j, RRch_{dca,j,k}, 8) \\
 Dfc1_{j,k} &= Cdc_{FCG}(RRch_{dca,j,k}, 1, Pt_{dca,j,k}, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}, Pt_{dcsra,j,k}, Peu_k, Ya(E_d_j), Mta_j, \eta_{a_{cc_j}}) \\
 Dfc2_{j,k} &= Cdc_{FCG}(RRch_{dca,j,k}, 2, Pt_{dca,j,k}, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}, Pt_{dcsra,j,k}, Peu_k, Ya(E_d_j), Mta_j, \eta_{a_{cc_j}}) \\
 Dfc4_{j,k} &= Cdc_{FCG}(RRch_{dca,j,k}, 4, Pt_{dca,j,k}, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}, Pt_{dcsra,j,k}, Peu_k, Ya(E_d_j), Mta_j, \eta_{a_{cc_j}}) \\
 Dfc8_{j,k} &= Cdc_{FCG}(RRch_{dca,j,k}, 8, Pt_{dca,j,k}, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}, Pt_{dcsra,j,k}, Peu_k, Ya(E_d_j), Mta_j, \eta_{a_{cc_j}}) \\
 Dsp1_{j,k} &= Cdc_{SPG}(1, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}) & Dsp2_{j,k} &= Cdc_{SPG}(2, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}) \\
 Dsp4_{j,k} &= Cdc_{SPG}(4, Pt_{dcsa,j,k}, Pt_{dcdca,j,k}) & Dsp8_{j,k} &= Cdc_{SPG}(8, Pt_{dcsa,j,k}, Pt_{dcdca,j,k})
 \end{aligned}$$

VIII. COST OF ELECTRICITY - the figure of merit which is to be minimized in this economic assessment is the levelized (constant FY 93dollar) cost of electricity (cents/kWehr), and the cost of hydrogen (CoH, \$/GJ) for cases using the electricity to produce hydrogen through electrolysis. The CoE and corresponding CoH is minimized with respect to the driver energy Ed , for each case (combination of driver, type of target gain curve, and energy conversion system), and for each combination of unit size and number of units. The CoE is given by the following function of the total direct capital cost $C_{TOT} = C_{DRG} + C_{FCG} + C_{SPG}$, the sum of the direct capital costs of the driver, fusion chamber, and steam plant groups in millions of constant FY 1993 dollars.

Annual charges for operations and scheduled component replacement (OM_SCR) are taken as a fixed percentage

$$OM_SCR = 0.03$$

of the total direct capital costs, plus an extra charge for higher target factory O&M costs, as noted below. The factor of two lower 3% O&M charges compared to the 6 % of direct costs assumed in the final HYLIFE-II report is to credit lower maintenance required for all-liquid walls in HYLIFE-II, compared to other fusion designs with solid first walls. Target factory O&M costs are expected to be much higher than 3 % of the target fab direct costs, and the extra is added as a function (OM_{TF} or $1.5*OM_{TF}$ without and with direct conversion) of the target production rate.

Constant dollar fixed charge rate: FCR = 0.0966 Indirect cost multiplier: IDC = 1.936 Availability: Fa = 0.85

The general constant dollar CoE is expressed in the functional form, cents /kWehr, 1993 \$, for C_{TOT} in 1993\$:

$$\text{CoE}(C_{\text{TOT}}, \text{Nu}, \text{Peu}, \text{RR}) = \frac{C_{\text{TOT}}(\text{IDC} \cdot \text{FCR} + \text{OM_SCR}) + \text{OM}_{\text{TF}}(\text{RR}, \text{Nu})}{0.0876 \cdot \text{Nu} \cdot \text{Peu} \cdot \text{Fa}} + \text{CoE}_{\text{FUEL}} + \text{CoE}_{\text{DECOM}}$$

CALCULATION OF CoE MATRICES (Ed_j x Peu_k) BY CASES

Nomenclature: the CoE's are calculated as matrices in the form coe[capital letter][number]_{j,k}, where [capital letter] is the letter designating the case (A, B, C, or D), and where the [number] is the number of units Nu. The COE is calculated for each driver energy Ed_j, and each net power/unit Peu_k. Values valid only for driver energies above Ed > 3.5MJ with conventional gains, or > 1 MJ with advanced targets, or above driver energies required for rep rates RR < 15 Hz.

CASE (A) - CONVENTIONAL TARGET GAINS WITH CONVENTIONAL STEAM BOP

$$\text{coeA1}_{j,k} = \text{CoE}(\text{Adr1}_{j,k} + \text{Afc1}_{j,k} + \text{Asp1}_{j,k}, 1, \text{Peu}_k, \text{RRch}_{j,k})$$

$$\text{coeA2}_{j,k} = \text{CoE}(\text{Adr2}_{j,k} + \text{Afc2}_{j,k} + \text{Asp2}_{j,k}, 2, \text{Peu}_k, \text{RRch}_{j,k})$$

$$\text{coeA4}_{j,k} = \text{CoE}(\text{Adr4}_{j,k} + \text{Afc4}_{j,k} + \text{Asp4}_{j,k}, 4, \text{Peu}_k, \text{RRch}_{j,k})$$

$$\text{coeA8}_{j,k} = \text{CoE}(\text{Adr8}_{j,k} + \text{Afc8}_{j,k} + \text{Asp8}_{j,k}, 8, \text{Peu}_k, \text{RRch}_{j,k})$$

CASE (B) - ADVANCED TARGET GAINS WITH CONVENTIONAL STEAM BOP

$$\text{coeB1}_{j,k} = \text{CoE}(\text{Bdr1}_{j,k} + \text{Bfc1}_{j,k} + \text{Bsp1}_{j,k}, 1, \text{Peu}_k, \text{RRch}_{a,j,k})$$

$$\text{coeB2}_{j,k} = \text{CoE}(\text{Bdr2}_{j,k} + \text{Bfc2}_{j,k} + \text{Bsp2}_{j,k}, 2, \text{Peu}_k, \text{RRch}_{a,j,k})$$

$$\text{coeB4}_{j,k} = \text{CoE}(\text{Bdr4}_{j,k} + \text{Bfc4}_{j,k} + \text{Bsp4}_{j,k}, 4, \text{Peu}_k, \text{RRch}_{a,j,k})$$

$$\text{coeB8}_{j,k} = \text{CoE}(\text{Bdr8}_{j,k} + \text{Bfc8}_{j,k} + \text{Bsp8}_{j,k}, 8, \text{Peu}_k, \text{RRch}_{a,j,k})$$

CASE (C) - CONVENTIONAL TARGET GAINS WITH MHD+STEAM COMBINED-CYCLE BOP

$$\text{coeC1}_{j,k} = \text{CoE}(\text{Cdr1}_{j,k} + \text{Cfc1}_{j,k} + \text{Csp1}_{j,k}, 1, \text{Peu}_k, \text{RRch}_{dc,j,k})$$

$$\text{coeC2}_{j,k} = \text{CoE}(\text{Cdr2}_{j,k} + \text{Cfc2}_{j,k} + \text{Csp2}_{j,k}, 2, \text{Peu}_k, \text{RRch}_{dc,j,k})$$

$$\text{coeC4}_{j,k} = \text{CoE}(\text{Cdr4}_{j,k} + \text{Cfc4}_{j,k} + \text{Csp4}_{j,k}, 4, \text{Peu}_k, \text{RRch}_{dc,j,k})$$

$$\text{coeC8}_{j,k} = \text{CoE}(\text{Cdr8}_{j,k} + \text{Cfc8}_{j,k} + \text{Csp8}_{j,k}, 8, \text{Peu}_k, \text{RRch}_{dc,j,k})$$

CASE (D) - ADVANCED TARGET GAINS WITH MHD+STEAM COMBINED-CYCLE BOP

$$\text{coeD1}_{j,k} = \text{CoE}(\text{Ddr1}_{j,k} + \text{Dfc1}_{j,k} + \text{Dsp1}_{j,k}, 1, \text{Peu}_k, \text{RRch}_{dca,j,k})$$

$$\text{coeD2}_{j,k} = \text{CoE}(\text{Ddr2}_{j,k} + \text{Dfc2}_{j,k} + \text{Dsp2}_{j,k}, 2, \text{Peu}_k, \text{RRch}_{dca,j,k})$$

$$\text{coeD4}_{j,k} = \text{CoE}(\text{Ddr4}_{j,k} + \text{Dfc4}_{j,k} + \text{Dsp4}_{j,k}, 4, \text{Peu}_k, \text{RRch}_{dca,j,k})$$

$$\text{coeD8}_{j,k} = \text{CoE}(\text{Ddr8}_{j,k} + \text{Dfc8}_{j,k} + \text{Dsp8}_{j,k}, 8, \text{Peu}_k, \text{RRch}_{dca,j,k})$$

Fig. 15 Summary of CoE (1993 cents/kWehr) as a function of driver energy for multi-unit plants of size suitable for hydrogen production by electrolysis (all 8-GWe plants with four-2000 MWe units), for case A-conventional gains and steam plant (solid line), case B-advanced gains with steam plant (dotted line), case C-conventional gains with MHD+steam combined cycle plant (dashed line), and for case D-advanced gains with MHD+steam combined cycle plant (dot-dashed line). Slope changes on the left-rising-sides of the CoE curves for cases C and D are due to the clipping of the bypass pumping powers at $RR = 15$ Hz for lower driver energies. The additional slope change at $Ed = 5.5$ MJ for case C is due to N_{sp} changing from 2 to 1 going to higher Ed where P_t to steam plant is less. Note the main effect of advanced target gains (cases B and D) shifts the CoE minima to lower driver energies ~ 3 -4 MJ, but since driver component costs are relatively small for large plants, the CoE minima with advanced targets are not much lower than for conventional gains. However, the advantage of advanced gains would be greater for staged deployment of such a plant, since the relative driver capital savings would be considerably larger for the first unit. The advanced gain CoE's are higher at large Ed because of very large yields (several GJ), causing large cost increases in the fusion chamber.

Analysis of driver-energy-dependence of performance and cost for the reference electric plant (one unit @1 GWe, case A) and for the reference hydrogen plant (four units @ 2GWe, case A):

$$SP_{e_j} = Asp1_{j,3} \cdot (IDC \cdot FCR + OM_SCR) \cdot (0.0876 \cdot 1 \cdot Peu_3 \cdot Fa)^{-1} \quad [\text{Electric plant ref. case} = "e"]$$

$$FC_{e_j} = [Afc1_{j,3} \cdot (IDC \cdot FCR + OM_SCR) + OM_{TF}(RRch_{j,3}, 1)] \cdot (0.0876 \cdot 1 \cdot Peu_3 \cdot Fa)^{-1} + CoE_{DECOM} + CoE_{FUEL}$$

$$DR_{e_j} = Adr1_{j,3} \cdot (IDC \cdot FCR + OM_SCR) \cdot (0.0876 \cdot 1 \cdot Peu_3 \cdot Fa)^{-1} \quad [\text{Contributions of target factory, driver group, and fusion chamber capital and operating costs to CoE}]$$

$$SP_{h_j} = Asp4_{j,4} \cdot (IDC \cdot FCR + OM_SCR) \cdot (0.0876 \cdot 4 \cdot Peu_4 \cdot Fa)^{-1} \quad [\text{Hydrogen plant ref. case} = "h"]$$

$$FC_{h_j} = [Afc4_{j,4} \cdot (IDC \cdot FCR + OM_SCR) + OM_{TF}(RRch_{j,4}, 4)] \cdot (0.0876 \cdot 4 \cdot Peu_4 \cdot Fa)^{-1} + CoE_{DECOM} + CoE_{FUEL}$$

$$DR_{h_j} = Adr4_{j,4} \cdot (IDC \cdot FCR + OM_SCR) \cdot (0.0876 \cdot 4 \cdot Peu_4 \cdot Fa)^{-1}$$

$$\begin{bmatrix} coeA13ref_{j,1} \\ coeA13ref_{j,2} \\ coeA13ref_{j,3} \\ coeA13ref_{j,4} \end{bmatrix} = \begin{bmatrix} SP_{e_j} \\ FC_{e_j} \\ DR_{e_j} \\ Ed_j \end{bmatrix} \quad \begin{bmatrix} coeA44ref_{j,1} \\ coeA44ref_{j,2} \\ coeA44ref_{j,3} \\ coeA44ref_{j,4} \end{bmatrix} = \begin{bmatrix} SP_{h_j} \\ FC_{h_j} \\ DR_{h_j} \\ Ed_j \end{bmatrix} \quad \begin{bmatrix} parA13ref_{j,1} \\ parA13ref_{j,2} \\ parA13ref_{j,3} \\ parA13ref_{j,4} \\ parA13ref_{j,5} \end{bmatrix} = \begin{bmatrix} Pt_{j,3} \cdot 1000^{-1} \\ RRch_{j,3} \\ Y(Ed_j) \cdot 100^{-1} \\ freq_{j,3} \cdot 100 \\ Ed_j \end{bmatrix} \quad \begin{bmatrix} parA44ref_{j,1} \\ parA44ref_{j,2} \\ parA44ref_{j,3} \\ parA44ref_{j,4} \\ parA44ref_{j,5} \end{bmatrix} = \begin{bmatrix} 4 \cdot Pt_{j,4} \cdot 1000^{-1} \\ RRch_{j,4} \\ Y(Ed_j) \cdot 100^{-1} \\ freq_{j,4} \cdot 100 \\ Ed_j \end{bmatrix}$$

Fig. 16 Key operating parameters versus driver energy Ed in MJ for the reference case 8 GWe H_2 plant : total thermal power in GW_{th} for four- 2000 MWe units (solid line), fusion chamber rep rate (dotted line) in Hz per chamber, target fusion yield in hundreds of MJ (dashed line), and recirculating power fraction in percent of gross electric (dash-dot line).

Fig. 17 Contributions of the steam plant, fusion chamber, and driver groups of subsystems to the total CoE (1993 cents/kWehr) versus driver energy Ed for the reference H_2 plant of four-2000 MWe units. The fusion chamber has a minimum vs Ed due to declining target factory costs and thermal power (Fig. 16) with Ed (lower rep rate) and due to rising fusion chamber costs with larger Ed and associated fusion yields.

MINIMIZING COE WITH RESPECT TO DRIVER ENERGY The following section uses MathCAD's matrix operators to find the minimum $\text{coeX}_{\#j,k}(\text{Ed}_j, \text{Peu}_k)$ for each case.

CASE (A) - CONVENTIONAL TARGET GAIN, CONVENTIONAL STEAM BOP

Case A One-unit plants

$$\begin{aligned} \text{coeA11}_j &:= \text{coeA1}_{j,1} & \text{coeA}_{1,1} &:= \min(\text{coeA11}) & \text{mA11}_j &:= \text{until}(0.999 \cdot \text{coeA11}_j - \text{coeA}_{1,1}, 1) & \text{jA}_{1,1} &:= \text{last}(\text{mA11}) & 250 \text{ MWe/unit} \\ \text{coeA12}_j &:= \text{coeA1}_{j,2} & \text{coeA}_{1,2} &:= \min(\text{coeA12}) & \text{mA12}_j &:= \text{until}(0.999 \cdot \text{coeA12}_j - \text{coeA}_{1,2}, 1) & \text{jA}_{1,2} &:= \text{last}(\text{mA12}) & 500 \text{ MWe/unit} \\ \text{coeA13}_j &:= \text{coeA1}_{j,3} & \text{coeA}_{1,3} &:= \min(\text{coeA13}) & \text{mA13}_j &:= \text{until}(0.999 \cdot \text{coeA13}_j - \text{coeA}_{1,3}, 1) & \text{jA}_{1,3} &:= \text{last}(\text{mA13}) & 1000 \text{ MWe/unit} \\ \text{coeA14}_j &:= \text{coeA1}_{j,4} & \text{coeA}_{1,4} &:= \min(\text{coeA14}) & \text{mA14}_j &:= \text{until}(0.999 \cdot \text{coeA14}_j - \text{coeA}_{1,4}, 1) & \text{jA}_{1,4} &:= \text{last}(\text{mA14}) & 2000 \text{ MWe/unit} \end{aligned}$$

Case A Two-unit plants

$$\begin{aligned} \text{coeA21}_j &:= \text{coeA2}_{j,1} & \text{coeA}_{2,1} &:= \min(\text{coeA21}) & \text{mA21}_j &:= \text{until}(0.999 \cdot \text{coeA21}_j - \text{coeA}_{2,1}, 1) & \text{jA}_{2,1} &:= \text{last}(\text{mA21}) & 250 \text{ MWe/unit} \\ \text{coeA22}_j &:= \text{coeA2}_{j,2} & \text{coeA}_{2,2} &:= \min(\text{coeA22}) & \text{mA22}_j &:= \text{until}(0.999 \cdot \text{coeA22}_j - \text{coeA}_{2,2}, 1) & \text{jA}_{2,2} &:= \text{last}(\text{mA22}) & 500 \text{ MWe/unit} \\ \text{coeA23}_j &:= \text{coeA2}_{j,3} & \text{coeA}_{2,3} &:= \min(\text{coeA23}) & \text{mA23}_j &:= \text{until}(0.999 \cdot \text{coeA23}_j - \text{coeA}_{2,3}, 1) & \text{jA}_{2,3} &:= \text{last}(\text{mA23}) & 1000 \text{ MWe/unit} \\ \text{coeA24}_j &:= \text{coeA2}_{j,4} & \text{coeA}_{2,4} &:= \min(\text{coeA24}) & \text{mA24}_j &:= \text{until}(0.999 \cdot \text{coeA24}_j - \text{coeA}_{2,4}, 1) & \text{jA}_{2,4} &:= \text{last}(\text{mA24}) & 2000 \text{ MWe/unit} \end{aligned}$$

Case A Four-unit plants

$$\begin{aligned} \text{coeA41}_j &:= \text{coeA4}_{j,1} & \text{coeA}_{3,1} &:= \min(\text{coeA41}) & \text{mA41}_j &:= \text{until}(0.999 \cdot \text{coeA41}_j - \text{coeA}_{3,1}, 1) & \text{jA}_{3,1} &:= \text{last}(\text{mA41}) & 250 \text{ MWe/unit} \\ \text{coeA42}_j &:= \text{coeA4}_{j,2} & \text{coeA}_{3,2} &:= \min(\text{coeA42}) & \text{mA42}_j &:= \text{until}(0.999 \cdot \text{coeA42}_j - \text{coeA}_{3,2}, 1) & \text{jA}_{3,2} &:= \text{last}(\text{mA42}) & 500 \text{ MWe/unit} \\ \text{coeA43}_j &:= \text{coeA4}_{j,3} & \text{coeA}_{3,3} &:= \min(\text{coeA43}) & \text{mA43}_j &:= \text{until}(0.999 \cdot \text{coeA43}_j - \text{coeA}_{3,3}, 1) & \text{jA}_{3,3} &:= \text{last}(\text{mA43}) & 1000 \text{ MWe/unit} \\ \text{coeA44}_j &:= \text{coeA4}_{j,4} & \text{coeA}_{3,4} &:= \min(\text{coeA44}) & \text{mA44}_j &:= \text{until}(0.999 \cdot \text{coeA44}_j - \text{coeA}_{3,4}, 1) & \text{jA}_{3,4} &:= \text{last}(\text{mA44}) & 2000 \text{ MWe/unit} \end{aligned}$$

Case A Eight-unit plants

$$\begin{aligned} \text{coeA81}_j &:= \text{coeA8}_{j,1} & \text{coeA}_{4,1} &:= \min(\text{coeA81}) & \text{mA81}_j &:= \text{until}(0.999 \cdot \text{coeA81}_j - \text{coeA}_{4,1}, 1) & \text{jA}_{4,1} &:= \text{last}(\text{mA81}) & 250 \text{ MWe/unit} \\ \text{coeA82}_j &:= \text{coeA8}_{j,2} & \text{coeA}_{4,2} &:= \min(\text{coeA82}) & \text{mA82}_j &:= \text{until}(0.999 \cdot \text{coeA82}_j - \text{coeA}_{4,2}, 1) & \text{jA}_{4,2} &:= \text{last}(\text{mA82}) & 500 \text{ MWe/unit} \\ \text{coeA83}_j &:= \text{coeA8}_{j,3} & \text{coeA}_{4,3} &:= \min(\text{coeA83}) & \text{mA83}_j &:= \text{until}(0.999 \cdot \text{coeA83}_j - \text{coeA}_{4,3}, 1) & \text{jA}_{4,3} &:= \text{last}(\text{mA83}) & 1000 \text{ MWe/unit} \\ \text{coeA84}_j &:= \text{coeA8}_{j,4} & \text{coeA}_{4,4} &:= \min(\text{coeA84}) & \text{mA84}_j &:= \text{until}(0.999 \cdot \text{coeA84}_j - \text{coeA}_{4,4}, 1) & \text{jA}_{4,4} &:= \text{last}(\text{mA84}) & 2000 \text{ MWe/unit} \end{aligned}$$

CASE A Summary-Optimized results for performance parameters: $\text{coe}_A := \text{coeA}$

For net powers $\text{Peu} = 250 \quad 500 \quad 1000 \quad 2000 \text{ MWe/unit}$ Optimal CoE, cents/kWehr Optimal driver energy indic:

$$\begin{aligned} \text{Total plant net power MWe} \quad \text{Pn} &= \begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix} & \begin{matrix} 1\text{-unit} \\ 2\text{-units} \\ 4\text{-units} \\ 8\text{-units} \end{matrix} & \text{coe}_A = \begin{bmatrix} 11.33 & 7.18 & 4.69 & 3.47 \\ 7.9 & 5.18 & 3.5 & 2.69 \\ 6.03 & 4.09 & 2.84 & 2.26 \\ 4.99 & 3.47 & 2.46 & 2.01 \end{bmatrix} & \text{jA} = \begin{bmatrix} 22 & 25 & 29 & 35 \\ 24 & 27 & 32 & 39 \\ 25 & 29 & 34 & 41 \\ 26 & 30 & 35 & 42 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} \text{Optimal driver energy (MJ):} \quad \text{Ed}_{A_{i,k}} &= \text{Ed}_{jA_{i,k}} & \text{Optimal target gain:} \quad G_{A_{i,k}} &:= G(\text{Ed}_{A_{i,k}}) & \text{Optimal target yield (MJ)} \quad Y_{A_{i,k}} &:= Y(\text{Ed}_{A_{i,k}}) \\ \text{Ed}_A &= \begin{bmatrix} 4.2 & 5 & 6 & 7.7 \\ 4.7 & 5.5 & 6.8 & 8.9 \\ 5 & 6 & 7.4 & 9.5 \\ 5.2 & 6.3 & 7.7 & 9.8 \end{bmatrix} & G_A &= \begin{bmatrix} 58 & 70 & 84 & 102 \\ 66 & 78 & 93 & 112 \\ 70 & 84 & 99 & 118 \\ 74 & 87 & 102 & 120 \end{bmatrix} & Y_A &= \begin{bmatrix} 246 & 351 & 508 & 783 \\ 314 & 427 & 639 & 998 \\ 351 & 508 & 733 & 1119 \\ 388 & 551 & 783 & 1183 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} \text{Optimal rep rate (Hz/unit):} \quad \text{RRch}_{A_{i,k}} &= \text{RRch}_{jA_{i,k},k} & \text{Optimal thermal power MW/unit:} \quad \text{Pt}_{A_{i,k}} &= \text{Pt}_{jA_{i,k},k} & \text{Optimal recirc. power MWe/unit:} \quad \text{frec}_{A_{i,k}} &= \text{frec}_{jA_{i,k},k} \\ \text{RRch}_A &= \begin{bmatrix} 2.4 & 3.2 & 4.3 & 5.5 \\ 1.8 & 2.6 & 3.4 & 4.2 \\ 1.6 & 2.2 & 2.9 & 3.8 \\ 1.4 & 2 & 2.7 & 3.6 \end{bmatrix} & \text{Pt}_A &= \begin{bmatrix} 695 & 1333 & 2592 & 5078 \\ 681 & 1316 & 2564 & 5034 \\ 676 & 1304 & 2550 & 5017 \\ 671 & 1299 & 2544 & 5009 \end{bmatrix} & \text{frec}_A &= \begin{bmatrix} 0.163 & 0.127 & 0.103 & 0.084 \\ 0.146 & 0.116 & 0.093 & 0.076 \\ 0.139 & 0.108 & 0.088 & 0.073 \\ 0.134 & 0.105 & 0.086 & 0.071 \end{bmatrix} \end{aligned}$$

CASE (A) SUMMARY--OPTIMAL DIRECT CAPITAL COSTS (M-93\$)

$$\begin{aligned}
 Cdr_{A_{1,k}} &:= A_{dr1,jA_{1,k,k}} & Cfc_{A_{1,k}} &:= A_{fc1,jA_{1,k,k}} & Csp_{A_{1,k}} &:= A_{sp1,jA_{1,k,k}} \\
 Cdr_{A_{2,k}} &:= A_{dr2,jA_{2,k,k}} & Cfc_{A_{2,k}} &:= A_{fc2,jA_{2,k,k}} & Csp_{A_{2,k}} &:= A_{sp2,jA_{2,k,k}} \\
 Cdr_{A_{3,k}} &:= A_{dr4,jA_{3,k,k}} & Cfc_{A_{3,k}} &:= A_{fc4,jA_{3,k,k}} & Csp_{A_{3,k}} &:= A_{sp4,jA_{3,k,k}} \\
 Cdr_{A_{4,k}} &:= A_{dr8,jA_{4,k,k}} & Cfc_{A_{4,k}} &:= A_{fc8,jA_{4,k,k}} & Csp_{A_{4,k}} &:= A_{sp8,jA_{4,k,k}}
 \end{aligned}$$

Driver Group Costs	Fusion Chamber Group Costs	Steam Plant Group Costs
$Cdr_A = \begin{bmatrix} 443 & 482 & 532 & 601 \\ 494 & 540 & 604 & 689 \\ 565 & 626 & 705 & 808 \\ 684 & 761 & 864 & 996 \end{bmatrix}$	$Cfc_A = \begin{bmatrix} 287 & 408 & 574 & 964 \\ 465 & 668 & 940 & 1600 \\ 813 & 1169 & 1653 & 2841 \\ 1481 & 2139 & 3030 & 5240 \end{bmatrix}$	$Csp_A = \begin{bmatrix} 188 & 275 & 412 & 681 \\ 326 & 477 & 718 & 1187 \\ 595 & 870 & 1311 & 2171 \\ 1116 & 1633 & 2463 & 4081 \end{bmatrix}$

$$Ctd_A := Cdr_A + Cfc_A + Csp_A$$

Total Direct Costs	For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000 \text{ MWe/unit} \quad \rightarrow$				
$Ctd_A = \begin{bmatrix} 918 & 1164 & 1519 & 2247 \\ 1285 & 1685 & 2262 & 3477 \\ 1973 & 2665 & 3669 & 5820 \\ 3281 & 4534 & 6357 & 10317 \end{bmatrix}$	<table style="display: inline-table; vertical-align: middle;"> <tr> <td style="text-align: right;">Total plant net power MWe</td> <td style="text-align: center;">$P_n =$</td> <td style="text-align: left;"> $\begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix}$ </td> <td style="text-align: left;"> <div style="display: flex; flex-direction: column; align-items: center;"> <div>1-unit</div> <div>2-units</div> <div>4-units</div> <div>8-units</div> </div> </td> </tr> </table>	Total plant net power MWe	$P_n =$	$\begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix}$	<div style="display: flex; flex-direction: column; align-items: center;"> <div>1-unit</div> <div>2-units</div> <div>4-units</div> <div>8-units</div> </div>
Total plant net power MWe	$P_n =$	$\begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix}$	<div style="display: flex; flex-direction: column; align-items: center;"> <div>1-unit</div> <div>2-units</div> <div>4-units</div> <div>8-units</div> </div>		

Miscellaneous

Bypass Pump Power (total for plant)

$$Pbp_{A_{i,k}} := P_{bpb} (RRch_{jA_{i,k,k}}, Nu_i)$$

$$Pbp_A = \begin{bmatrix} 12 & 15 & 18 & 22 \\ 23 & 26 & 30 & 36 \\ 44 & 48 & 56 & 65 \\ 85 & 93 & 107 & 126 \end{bmatrix}$$

Driver Power (total for plant)

$$PHI_{A_{i,k}} := P_{HI} (Ed_{jA_{i,k,k}}, RRch_{jA_{i,k,k}}, Nu_i)$$

$$PHI_A = \begin{bmatrix} 28 & 43 & 67 & 102 \\ 47 & 75 & 115 & 177 \\ 87 & 134 & 212 & 330 \\ 162 & 254 & 408 & 639 \end{bmatrix}$$

Target Factory Direct Costs

$$CTF_{A_{i,k}} := C_{TFE} (RRch_{jA_{i,k,k}}, Nu_i, Pt_{jA_{i,k,k}}, \eta_{spp})$$

$$CTF_A = \begin{bmatrix} 31 & 38 & 47 & 56 \\ 40 & 51 & 63 & 77 \\ 58 & 71 & 90 & 113 \\ 84 & 106 & 137 & 173 \end{bmatrix}$$

Fusion Chamber Direct Costs

$$CFC_{A_{i,k}} := C_{FC} (Nu_i, Pt_{jA_{i,k,k}}, Y(Ed_{jA_{i,k,k}}))$$

$$CFC_A = \begin{bmatrix} 16 & 24 & 38 & 62 \\ 33 & 48 & 76 & 125 \\ 65 & 99 & 153 & 246 \\ 132 & 198 & 300 & 479 \end{bmatrix}$$

COST ACCOUNT SUMMARY— One-1000 MWe-unit and four-2000 MWe-unit plants . (Direct costs in M-93S)

c = 29

h = 41

HYLIF

ref (2)

ACCT. ITEM	[1GWe reference electric plant]	[8 GWe reference hydrogen plant]	
20 Land and land rights	$C_{1,1} = C_{LLR}(1)$ $C_{1,1} = 11.7$	$C_{1,2} = C_{LLR}(4)$ $C_{1,2} = 37.4$	11
21 Structures	$C_{2,1} = \left[\begin{array}{l} C_{DRB}(Ed_e) \dots \\ + C_{FCB}(1, Pt_{e,3}, \eta_{spp}) \dots \\ + C_{TFB}(RRch_{e,3}, 1) \dots \\ + C_{SPB}(1, Pt_{e,3}) \end{array} \right]$ $C_{2,1} = 159.6$	$C_{2,2} = \left[\begin{array}{l} C_{DRB}(Ed_h) \dots \\ + C_{FCB}(4, Pt_{h,4}, \eta_{spp}) \dots \\ + C_{TFB}(RRch_{h,4}, 4) \dots \\ + C_{SPB}(4, Pt_{h,4}) \end{array} \right]$ $C_{2,2} = 613.4$	129.2
22 Fusion Plant Equipment			
22.1 Fusion chamber equip. Fusion chamber	$C_{3,1} = C_{FC}(1, Pt_{e,3}, Y(Ed_e))$ $C_{3,1} = 37.9$	$C_{3,2} = C_{FC}(4, Pt_{h,4}, Y(Ed_h))$ $C_{3,2} = 245.6$	43.2
Bypass pumps	$C_{4,1} = C_{BPP}(RRch_{e,3}, 1)$ $C_{4,1} = 42.5$	$C_{4,2} = C_{BPP}(RRch_{h,4}, 4)$ $C_{4,2} = 123.7$	82.7
Bypass pipes	$C_{5,1} = C_{BPPipes}(1, Pt_{e,3})$ $C_{5,1} = 10$	$C_{5,2} = C_{BPPipes}(4, Pt_{h,4})$ $C_{5,2} = 50.6$	13.8
22.2 Flibe coolant	$C_{6,1} = C_{Flibe}(RRch_{e,3}, 1, Pt_{e,3})$ $C_{6,1} = 68.9$	$C_{6,2} = C_{Flibe}(RRch_{h,4}, 4, Pt_{h,4})$ $C_{6,2} = 341.3$	102.6
22.3 Vacuum system (in acct. 22.5)			
22.4 Target factory equip.	$C_{7,1} = C_{TFE}(RRch_{e,3}, 1, Pt_{e,3}, \eta_{spp})$ $C_{7,1} = 46.5$	$C_{7,2} = C_{TFE}(RRch_{h,4}, 4, Pt_{h,4}, \eta_{spp})$ $C_{7,2} = 113.1$	51.4
22.5 Tritium management sys.	$C_{8,1} = C_{TMS}(1, Pt_{e,3})$ $C_{8,1} = 97.5$	$C_{8,2} = C_{TMS}(4, Pt_{h,4})$ $C_{8,2} = 544.2$	92.0
22.6 Shielding (in acct. 21)			
22.7 Heat transport system			
Coolant piping	$C_{9,1} = C_{CLP}(1, Pt_{e,3})$ $C_{9,1} = 11.6$	$C_{9,2} = C_{CLP}(4, Pt_{h,4})$ $C_{9,2} = 74.2$	10.8
Coolant valves & bellows	$C_{10,1} = C_{CVB}(1, Pt_{e,3})$ $C_{10,1} = 20.2$	$C_{10,2} = C_{CVB}(4, Pt_{h,4})$ $C_{10,2} = 129.7$	19.1
Pump and motors	$C_{11,1} = C_{CPM}(1, Pt_{e,3})$ $C_{11,1} = 40.3$	$C_{11,2} = C_{CPM}(4, Pt_{h,4})$ $C_{11,2} = 252.8$	37.1
Coolant cleanup plant	$C_{12,1} = C_{CCP}(1, Pt_{e,3})$ $C_{12,1} = 16.5$	$C_{12,2} = C_{CCP}(4, Pt_{h,4})$ $C_{12,2} = 102.5$	15.0
Steam separators	$C_{13,1} = C_{SS}(1, Pt_{e,3})$ $C_{13,1} = 10$	$C_{13,2} = C_{SS}(4, Pt_{h,4})$ $C_{13,2} = 62$	9.1
Water loop piping	$C_{14,1} = C_{WLP}(1, Pt_{e,3})$ $C_{14,1} = 0.2$	$C_{14,2} = C_{WLP}(4, Pt_{h,4})$ $C_{14,2} = 0.7$	0.2

ACCT. ITEM (CONTINUED)	[1 GWe reference electric plant]	[8 GWe reference hydrogen plant]	HYLIF ref (2)
Steam Generators	$C_{15,1} := C_{SG}(1, Pt_{e,3})$ $C_{15,1} = 72.4$	$C_{15,2} := C_{SG}(4, Pt_{h,4})$ $C_{15,2} = 458.7$	77.1
22.8 Remote Maintenance Equip.	$C_{16,1} := C_{RME}(1, Peu_3)$ $C_{16,1} = 53$	$C_{16,2} := C_{RME}(4, Peu_4)$ $C_{16,2} = 115.9$	100
23 Turbine Plant Equipment	$C_{17,1} := C_{TPE}(1, Pt_{e,3})$ $C_{17,1} = 194.3$	$C_{17,2} := C_{TPE}(4, Pt_{h,4})$ $C_{17,2} = 1069.5$	178.1
24 Electric Plant Equipment	$C_{18,1} := C_{EPE}(1, Pt_{e,3})$ $C_{18,1} = 65.2$	$C_{18,2} := C_{EPE}(4, Pt_{h,4})$ $C_{18,2} = 363.4$	60.6
25 Miscellaneous Plant Equipment	$C_{19,1} := C_{MPE}(1, Pt_{e,3})$ $C_{19,1} = 25.4$	$C_{19,2} := C_{MPE}(4, Pt_{h,4})$ $C_{19,2} = 142.2$	23.7
26 Main Heat Rejection System	$C_{20,1} := C_{MHRS}(1, Pt_{e,3})$ $C_{20,1} = 39.4$	$C_{20,2} := C_{MHRS}(4, Pt_{h,4})$ $C_{20,2} = 217.1$	36.1
27 Driver Equipment			--
27.1 Driver	$C_{21,1} := C_{HIB}(Ed_e, RRch_{e,3}, 1)$ $C_{21,1} = 468.7$	$C_{21,2} := C_{HIB}(Ed_h, RRch_{h,4}, 4)$ $C_{21,2} = 675.8$	570
27.2 Beam Transport	$C_{22,1} := C_{BSY}(1)$ $C_{22,1} = 22.6$	$C_{22,2} := C_{BSY}(4)$ $C_{22,2} = 72.6$	
28.3 Target Injector System	$C_{23,1} := C_{INJ}(RRch_{e,3}, 1)$ $C_{23,1} = 4.6$	$C_{23,2} := C_{INJ}(RRch_{h,4}, 4)$ $C_{23,2} = 13.4$	
<hr/>			
$n := 1..23$	$C_{24,1} := \sum_n C_{n,1}$	$C_{24,2} := \sum_n C_{n,2}$	
Total plant direct cost:	$C_{24,1} = 1518.7 \quad [M93 \$]$	$C_{24,2} = 5820 \quad [M93 \$]$	1654
Unit direct cost:	$C_{25,1} := C_{24,1} \cdot (Pn_{1,3})^{-1}$ $C_{25,1} = 1.519 \quad [\$/We]$	$C_{25,2} := C_{24,2} \cdot (Pn_{3,4})^{-1}$ $C_{25,2} = 0.728 \quad [\$/We]$	
CoE (cts/kWehr):	$C_{26,1} := coe A_{1,3}$ $C_{26,1} = 4.7$	$C_{26,2} := coe A_{3,4}$ $C_{26,2} = 2.3$	
CoH (\$/GJ):	$C_{27,1} := CoH_2(C_{26,1})$ $C_{27,1} = 19.1$	$C_{27,2} := CoH_2(C_{26,2})$ $C_{27,2} = 10.8$	

ECONOMY-OF-SCALE, for reference case A, single and multi-unit electricity and hydrogen plants:

$$ECON = \begin{bmatrix} coe_{A_{1,1}} & CoH_2(coe_{A_{1,1}}) & Pn_{1,1} \\ coe_{A_{1,2}} & CoH_2(coe_{A_{1,2}}) & Pn_{1,2} \\ coe_{A_{1,3}} & CoH_2(coe_{A_{1,3}}) & Pn_{1,3} \\ coe_{A_{1,4}} & CoH_2(coe_{A_{1,4}}) & Pn_{1,4} \\ coe_{A_{2,4}} & CoH_2(coe_{A_{2,4}}) & Pn_{2,4} \\ coe_{A_{3,4}} & CoH_2(coe_{A_{3,4}}) & Pn_{3,4} \\ coe_{A_{4,4}} & CoH_2(coe_{A_{4,4}}) & Pn_{4,4} \end{bmatrix}$$

$$ECON = \begin{bmatrix} 11.3 & 41.5 & 250 \\ 7.2 & 27.5 & 500 \\ 4.7 & 19.1 & 1000 \\ 3.5 & 14.9 & 2000 \\ 2.7 & 12.3 & 4000 \\ 2.3 & 10.8 & 8000 \\ 2 & 10 & 16000 \end{bmatrix} \quad s = 1..7$$

cts/ kWehr \$/ GJ MWe $CoE_s := (ECON^{<1>})_s$
 $CoH_s := (ECON^{<2>})_s$
 $Pnet_s := (ECON^{<3>})_s$

Fig. 18 CoE (in mills/kWehr, dotted line) and CoH (in \$/GJ, no tax, delivered, dashed line) as a function of plant output (economy-of-scale). Single unit plants are assumed for $Pnet < 2$ GWe, multiple-2 GWe unit plants for outputs above 2 GWe. Horizontal solid line marks CoH for 13.4 \$/GJ, where fuel cost per mile with hydrogen optimized engines equals that of gasoline powered vehicles. This occurs approximately at $Pnet \sim 3$ GWe.

Saving data in MathCAD PRN files:

WRITEPRN(CoeEd13A) := coeA13ref	WRITEPRN(CoeEd44A) := coeA44ref
WRITEPRN(EconA) := ECON	WRITEPRN(ParEd13A) := parA13ref
WRITEPRN(PnetA) := Pn	WRITEPRN(ParEd44A) := parA44ref
WRITEPRN(EdA) := Ed _A	WRITEPRN(CoeA) := coe _A
WRITEPRN(RRchA) := RRch _A	WRITEPRN(GA) := G _A
WRITEPRN(CdrA) := Cdr _A	WRITEPRN(PtA) := Pt _A
WRITEPRN(CspA) := Csp _A	WRITEPRN(CfcA) := Cfc _A
WRITEPRN(CTFA) := CTF _A	WRITEPRN(CtdA) := Ctd _A
	WRITEPRN(CFCHA) := CFC _A
	WRITEPRN(PbA) := j _A
	WRITEPRN(YA) := Y _A
	WRITEPRN(FrecA) := frec _A
	WRITEPRN(PbpA) := Pbp _A
	WRITEPRN(PHIA) := PHI _A
	WRITEPRN(CsumA) := C

CASE (B) - ADVANCED TARGET GAINS WITH CONVENTIONAL STEAM BOP

Case B One-unit plants

$\text{coeB11}_j := \text{coeB1}_{j,1}$	$\text{coeB}_{1,1} := \min(\text{coeB11})$	$\text{mB11}_j := \text{until}(0.999 \cdot \text{coeB11}_j - \text{coeB}_{1,1}, 1)$	$\text{jB}_{1,1} := \text{last}(\text{mB11})$	250 MWe/unit
$\text{coeB12}_j := \text{coeB1}_{j,2}$	$\text{coeB}_{1,2} := \min(\text{coeB12})$	$\text{mB12}_j := \text{until}(0.999 \cdot \text{coeB12}_j - \text{coeB}_{1,2}, 1)$	$\text{jB}_{1,2} := \text{last}(\text{mB12})$	500 MWe/unit
$\text{coeB13}_j := \text{coeB1}_{j,3}$	$\text{coeB}_{1,3} := \min(\text{coeB13})$	$\text{mB13}_j := \text{until}(0.999 \cdot \text{coeB13}_j - \text{coeB}_{1,3}, 1)$	$\text{jB}_{1,3} := \text{last}(\text{mB13})$	1000 MWe/unit
$\text{coeB14}_j := \text{coeB1}_{j,4}$	$\text{coeB}_{1,4} := \min(\text{coeB14})$	$\text{mB14}_j := \text{until}(0.999 \cdot \text{coeB14}_j - \text{coeB}_{1,4}, 1)$	$\text{jB}_{1,4} := \text{last}(\text{mB14})$	2000 MWe/unit

Case B Two-unit plants

$\text{coeB21}_j := \text{coeB2}_{j,1}$	$\text{coeB}_{2,1} := \min(\text{coeB21})$	$\text{mB21}_j := \text{until}(0.999 \cdot \text{coeB21}_j - \text{coeB}_{2,1}, 1)$	$\text{jB}_{2,1} := \text{last}(\text{mB21})$	250 MWe/unit
$\text{coeB22}_j := \text{coeB2}_{j,2}$	$\text{coeB}_{2,2} := \min(\text{coeB22})$	$\text{mB22}_j := \text{until}(0.999 \cdot \text{coeB22}_j - \text{coeB}_{2,2}, 1)$	$\text{jB}_{2,2} := \text{last}(\text{mB22})$	500 MWe/unit
$\text{coeB23}_j := \text{coeB2}_{j,3}$	$\text{coeB}_{2,3} := \min(\text{coeB23})$	$\text{mB23}_j := \text{until}(0.999 \cdot \text{coeB23}_j - \text{coeB}_{2,3}, 1)$	$\text{jB}_{2,3} := \text{last}(\text{mB23})$	1000 MWe/unit
$\text{coeB24}_j := \text{coeB2}_{j,4}$	$\text{coeB}_{2,4} := \min(\text{coeB24})$	$\text{mB24}_j := \text{until}(0.999 \cdot \text{coeB24}_j - \text{coeB}_{2,4}, 1)$	$\text{jB}_{2,4} := \text{last}(\text{mB24})$	2000 MWe/unit

Case B Four-unit plants

$\text{coeB41}_j := \text{coeB4}_{j,1}$	$\text{coeB}_{3,1} := \min(\text{coeB41})$	$\text{mB41}_j := \text{until}(0.999 \cdot \text{coeB41}_j - \text{coeB}_{3,1}, 1)$	$\text{jB}_{3,1} := \text{last}(\text{mB41})$	250 MWe/unit
$\text{coeB42}_j := \text{coeB4}_{j,2}$	$\text{coeB}_{3,2} := \min(\text{coeB42})$	$\text{mB42}_j := \text{until}(0.999 \cdot \text{coeB42}_j - \text{coeB}_{3,2}, 1)$	$\text{jB}_{3,2} := \text{last}(\text{mB42})$	500 MWe/unit
$\text{coeB43}_j := \text{coeB4}_{j,3}$	$\text{coeB}_{3,3} := \min(\text{coeB43})$	$\text{mB43}_j := \text{until}(0.999 \cdot \text{coeB43}_j - \text{coeB}_{3,3}, 1)$	$\text{jB}_{3,3} := \text{last}(\text{mB43})$	1000 MWe/unit
$\text{coeB44}_j := \text{coeB4}_{j,4}$	$\text{coeB}_{3,4} := \min(\text{coeB44})$	$\text{mB44}_j := \text{until}(0.999 \cdot \text{coeB44}_j - \text{coeB}_{3,4}, 1)$	$\text{jB}_{3,4} := \text{last}(\text{mB44})$	2000 MWe/unit

Case B Eight-unit plants

$\text{coeB81}_j := \text{coeB8}_{j,1}$	$\text{coeB}_{4,1} := \min(\text{coeB81})$	$\text{mB81}_j := \text{until}(0.999 \cdot \text{coeB81}_j - \text{coeB}_{4,1}, 1)$	$\text{jB}_{4,1} := \text{last}(\text{mB81})$	250 MWe/unit
$\text{coeB82}_j := \text{coeB8}_{j,2}$	$\text{coeB}_{4,2} := \min(\text{coeB82})$	$\text{mB82}_j := \text{until}(0.999 \cdot \text{coeB82}_j - \text{coeB}_{4,2}, 1)$	$\text{jB}_{4,2} := \text{last}(\text{mB82})$	500 MWe/unit
$\text{coeB83}_j := \text{coeB8}_{j,3}$	$\text{coeB}_{4,3} := \min(\text{coeB83})$	$\text{mB83}_j := \text{until}(0.999 \cdot \text{coeB83}_j - \text{coeB}_{4,3}, 1)$	$\text{jB}_{4,3} := \text{last}(\text{mB83})$	1000 MWe/unit
$\text{coeB84}_j := \text{coeB8}_{j,4}$	$\text{coeB}_{4,4} := \min(\text{coeB84})$	$\text{mB84}_j := \text{until}(0.999 \cdot \text{coeB84}_j - \text{coeB}_{4,4}, 1)$	$\text{jB}_{4,4} := \text{last}(\text{mB84})$	2000 MWe/unit

CASE B Summary-Optimized results for performance parameters: $\text{coeB} := \text{coeB}$

For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000$ MWe/ unit					Optimal CoE, cents/kWehr	Optimal driver energy indices:			
Total plant net power MWe $P_n =$	250	500	1000	2000	1-unit	$\text{coe}_B =$	$\text{j}_B =$	$\begin{bmatrix} 7 & 9 & 12 & 16 \\ 8 & 10 & 13 & 17 \\ 9 & 11 & 14 & 18 \\ 10 & 12 & 15 & 19 \end{bmatrix}$	
	500	1000	2000	4000	2-units				
	1000	2000	4000	8000	4-units				
	2000	4000	8000	16000	8-units				
Optimal driver energy (MJ): $\text{Ed}_{B_{i,k}} := \text{Ed}_{jB_{i,k}}$					Optimal target gain: $G_{B_{i,k}} := G_a(\text{Ed}_{B_{i,k}})$		Optimal target yield (MJ) $Y_{B_{i,k}} := Y_a(\text{Ed}_{B_{i,k}})$		
$\text{Ed}_B = \begin{bmatrix} 1.2 & 1.5 & 2.1 & 2.9 \\ 1.4 & 1.7 & 2.3 & 3.1 \\ 1.5 & 1.9 & 2.5 & 3.3 \\ 1.7 & 2.1 & 2.7 & 3.5 \end{bmatrix}$					$G_B = \begin{bmatrix} 179 & 207 & 243 & 285 \\ 193 & 219 & 254 & 295 \\ 207 & 231 & 265 & 304 \\ 219 & 243 & 275 & 314 \end{bmatrix}$		$Y_B = \begin{bmatrix} 218 & 317 & 503 & 820 \\ 265 & 374 & 574 & 911 \\ 317 & 436 & 651 & 1008 \\ 374 & 503 & 733 & 1109 \end{bmatrix}$		
Optimal rep rate (Hz/unit): $\text{RRch}_{B_{i,k}} := \text{RRch}_{ajB_{i,k},k}$					Optimal thermal power MW/unit: $\text{Pt}_{B_{i,k}} := \text{Pt}_{ajB_{i,k},k}$		Optimal recirc. power MWe/unit: $\text{frec}_{B_{i,k}} := \text{frec}_{ajB_{i,k},k}$		
$\text{RRch}_B = \begin{bmatrix} 2.5 & 3.4 & 4.2 & 5.1 \\ 2.1 & 2.9 & 3.7 & 4.6 \\ 1.7 & 2.4 & 3.2 & 4.1 \\ 1.5 & 2.1 & 2.9 & 3.7 \end{bmatrix}$					$\text{Pt}_B = \begin{bmatrix} 657 & 1277 & 2503 & 4939 \\ 651 & 1269 & 2494 & 4929 \\ 647 & 1264 & 2487 & 4920 \\ 644 & 1259 & 2481 & 4913 \end{bmatrix}$		$\text{frec}_B = \begin{bmatrix} 0.115 & 0.089 & 0.071 & 0.058 \\ 0.107 & 0.084 & 0.068 & 0.056 \\ 0.101 & 0.08 & 0.065 & 0.055 \\ 0.097 & 0.076 & 0.063 & 0.053 \end{bmatrix}$		

CASE (B) SUMMARY—OPTIMAL DIRECT CAPITAL COSTS (M-93\$)

$$Cdr_{B_{1,k}} = Bdr1_{jB_{1,k},k}$$

$$Cfc_{B_{1,k}} = Bfc1_{jB_{1,k},k}$$

$$Csp_{B_{1,k}} = Bsp1_{jB_{1,k},k}$$

$$Cdr_{B_{2,k}} = Bdr2_{jB_{2,k},k}$$

$$Cfc_{B_{2,k}} = Bfc2_{jB_{2,k},k}$$

$$Csp_{B_{2,k}} = Bsp2_{jB_{2,k},k}$$

$$Cdr_{B_{3,k}} = Bdr4_{jB_{3,k},k}$$

$$Cfc_{B_{3,k}} = Bfc4_{jB_{3,k},k}$$

$$Csp_{B_{3,k}} = Bsp4_{jB_{3,k},k}$$

$$Cdr_{B_{4,k}} = Bdr8_{jB_{4,k},k}$$

$$Cfc_{B_{4,k}} = Bfc8_{jB_{4,k},k}$$

$$Csp_{B_{4,k}} = Bsp8_{jB_{4,k},k}$$

Driver Group Costs

$$Cdr_B = \begin{bmatrix} 325 & 356 & 399 & 454 \\ 365 & 401 & 449 & 511 \\ 427 & 470 & 527 & 601 \\ 530 & 584 & 656 & 750 \end{bmatrix}$$

Fusion Chamber Group Costs

$$Cfc_B = \begin{bmatrix} 285 & 406 & 568 & 952 \\ 463 & 665 & 936 & 1592 \\ 805 & 1162 & 1643 & 2824 \\ 1465 & 2120 & 3005 & 5203 \end{bmatrix}$$

Steam Plant Group Costs

$$Csp_B = \begin{bmatrix} 183 & 268 & 403 & 670 \\ 318 & 467 & 705 & 1171 \\ 581 & 854 & 1290 & 2145 \\ 1091 & 1603 & 2424 & 4031 \end{bmatrix}$$

$$Ctd_B = Cdr_B + Cfc_B + Csp_B$$

Total Direct Costs

$$Ctd_B = \begin{bmatrix} 793 & 1030 & 1370 & 2075 \\ 1147 & 1533 & 2090 & 3275 \\ 1814 & 2486 & 3460 & 5570 \\ 3086 & 4307 & 6085 & 9984 \end{bmatrix}$$

For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000 \text{ MWe/unit} \quad \rightarrow$

$$\begin{array}{l} \text{Total plant} \\ \text{net power} \\ \text{MWe} \end{array} \quad P_n = \begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix} \begin{array}{l} \text{1-unit} \\ \text{2-units} \\ \text{4-units} \\ \text{8-units} \end{array}$$

Miscellaneous

Bypass Pump Power (total for plant)

$$Pbp_{B_{i,k}} = P_{bpb} (RRch_{ajB_{i,k},k}) \cdot Nu_i$$

$$Pbp_B = \begin{bmatrix} 13 & 15 & 18 & 21 \\ 24 & 27 & 32 & 38 \\ 44 & 51 & 59 & 70 \\ 85 & 95 & 110 & 130 \end{bmatrix}$$

Driver Power (total for plant)

$$PHI_{B_{i,k}} = P_{HI} (Ed_{jB_{i,k}}, RRch_{ajB_{i,k},k}) \cdot Nu_i$$

$$PHI_B = \begin{bmatrix} 12 & 19 & 29 & 45 \\ 21 & 35 & 55 & 86 \\ 38 & 64 & 102 & 164 \\ 70 & 118 & 193 & 312 \end{bmatrix}$$

Target Factory Direct Costs

$$CTF_{B_{i,k}} = C_{TFE} (RRch_{ajB_{i,k},k}, Nu_i, Pt_{ajB_{i,k},k}, \eta_{spp})$$

$$CTF_B = \begin{bmatrix} 32 & 39 & 46 & 54 \\ 43 & 54 & 65 & 79 \\ 59 & 76 & 95 & 118 \\ 84 & 110 & 140 & 177 \end{bmatrix}$$

Fusion Chamber Direct Costs

$$CFC_{B_{i,k}} = C_{FC} (Nu_i, Pt_{ajB_{i,k},k}, Ya(Ed_{jB_{i,k}}))$$

$$CFC_B = \begin{bmatrix} 14 & 22 & 37 & 63 \\ 29 & 44 & 71 & 117 \\ 60 & 88 & 140 & 229 \\ 127 & 184 & 285 & 457 \end{bmatrix}$$

CASE (C) - CONVENTIONAL TARGET GAINS WITH MHD+ STEAM COMBINED-CYCLE BOP

Case C One-unit plants

$\text{coeC11}_j = \text{coeC1}_{j,1}$	$\text{coeC}_{1,1} = \min(\text{coeC11})$	$\text{mC11}_j = \text{until}(0.999 \cdot \text{coeC11}_j - \text{coeC}_{1,1}, 1)$	$\text{jC}_{1,1} = \text{last}(\text{mC11})$	250 MWe/unit
$\text{coeC12}_j = \text{coeC1}_{j,2}$	$\text{coeC}_{1,2} = \min(\text{coeC12})$	$\text{mC12}_j = \text{until}(0.999 \cdot \text{coeC12}_j - \text{coeC}_{1,2}, 1)$	$\text{jC}_{1,2} = \text{last}(\text{mC12})$	500 MWe/unit
$\text{coeC13}_j = \text{coeC1}_{j,3}$	$\text{coeC}_{1,3} = \min(\text{coeC13})$	$\text{mC13}_j = \text{until}(0.999 \cdot \text{coeC13}_j - \text{coeC}_{1,3}, 1)$	$\text{jC}_{1,3} = \text{last}(\text{mC13})$	1000 MWe/unit
$\text{coeC14}_j = \text{coeC1}_{j,4}$	$\text{coeC}_{1,4} = \min(\text{coeC14})$	$\text{mC14}_j = \text{until}(0.999 \cdot \text{coeC14}_j - \text{coeC}_{1,4}, 1)$	$\text{jC}_{1,4} = \text{last}(\text{mC14})$	2000 MWe/unit

Case C Two-unit plants

$\text{coeC21}_j = \text{coeC2}_{j,1}$	$\text{coeC}_{2,1} = \min(\text{coeC21})$	$\text{mC21}_j = \text{until}(0.999 \cdot \text{coeC21}_j - \text{coeC}_{2,1}, 1)$	$\text{jC}_{2,1} = \text{last}(\text{mC21})$	250 MWe/unit
$\text{coeC22}_j = \text{coeC2}_{j,2}$	$\text{coeC}_{2,2} = \min(\text{coeC22})$	$\text{mC22}_j = \text{until}(0.999 \cdot \text{coeC22}_j - \text{coeC}_{2,2}, 1)$	$\text{jC}_{2,2} = \text{last}(\text{mC22})$	500 MWe/unit
$\text{coeC23}_j = \text{coeC2}_{j,3}$	$\text{coeC}_{2,3} = \min(\text{coeC23})$	$\text{mC23}_j = \text{until}(0.999 \cdot \text{coeC23}_j - \text{coeC}_{2,3}, 1)$	$\text{jC}_{2,3} = \text{last}(\text{mC23})$	1000 MWe/unit
$\text{coeC24}_j = \text{coeC2}_{j,4}$	$\text{coeC}_{2,4} = \min(\text{coeC24})$	$\text{mC24}_j = \text{until}(0.999 \cdot \text{coeC24}_j - \text{coeC}_{2,4}, 1)$	$\text{jC}_{2,4} = \text{last}(\text{mC24})$	2000 MWe/unit

Case C Four-unit plants

$\text{coeC41}_j = \text{coeC4}_{j,1}$	$\text{coeC}_{3,1} = \min(\text{coeC41})$	$\text{mC41}_j = \text{until}(0.999 \cdot \text{coeC41}_j - \text{coeC}_{3,1}, 1)$	$\text{jC}_{3,1} = \text{last}(\text{mC41})$	250 MWe/unit
$\text{coeC42}_j = \text{coeC4}_{j,2}$	$\text{coeC}_{3,2} = \min(\text{coeC42})$	$\text{mC42}_j = \text{until}(0.999 \cdot \text{coeC42}_j - \text{coeC}_{3,2}, 1)$	$\text{jC}_{3,2} = \text{last}(\text{mC42})$	500 MWe/unit
$\text{coeC43}_j = \text{coeC4}_{j,3}$	$\text{coeC}_{3,3} = \min(\text{coeC43})$	$\text{mC43}_j = \text{until}(0.999 \cdot \text{coeC43}_j - \text{coeC}_{3,3}, 1)$	$\text{jC}_{3,3} = \text{last}(\text{mC43})$	1000 MWe/unit
$\text{coeC44}_j = \text{coeC4}_{j,4}$	$\text{coeC}_{3,4} = \min(\text{coeC44})$	$\text{mC44}_j = \text{until}(0.999 \cdot \text{coeC44}_j - \text{coeC}_{3,4}, 1)$	$\text{jC}_{3,4} = \text{last}(\text{mC44})$	2000 MWe/unit

Case C Eight-unit plants

$\text{coeC81}_j = \text{coeC8}_{j,1}$	$\text{coeC}_{4,1} = \min(\text{coeC81})$	$\text{mC81}_j = \text{until}(0.999 \cdot \text{coeC81}_j - \text{coeC}_{4,1}, 1)$	$\text{jC}_{4,1} = \text{last}(\text{mC81})$	250 MWe/unit
$\text{coeC82}_j = \text{coeC8}_{j,2}$	$\text{coeC}_{4,2} = \min(\text{coeC82})$	$\text{mC82}_j = \text{until}(0.999 \cdot \text{coeC82}_j - \text{coeC}_{4,2}, 1)$	$\text{jC}_{4,2} = \text{last}(\text{mC82})$	500 MWe/unit
$\text{coeC83}_j = \text{coeC8}_{j,3}$	$\text{coeC}_{4,3} = \min(\text{coeC83})$	$\text{mC83}_j = \text{until}(0.999 \cdot \text{coeC83}_j - \text{coeC}_{4,3}, 1)$	$\text{jC}_{4,3} = \text{last}(\text{mC83})$	1000 MWe/unit
$\text{coeC84}_j = \text{coeC8}_{j,4}$	$\text{coeC}_{4,4} = \min(\text{coeC84})$	$\text{mC84}_j = \text{until}(0.999 \cdot \text{coeC84}_j - \text{coeC}_{4,4}, 1)$	$\text{jC}_{4,4} = \text{last}(\text{mC84})$	2000 MWe/unit

CASE C Summary- Optimized results for performance parameters: $\text{coe}_C = \text{coeC}$

For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000$ MWe/ unit					Optimal CoE, cents/kWehr				Optimal driver energy indic:								
Total plant net power MWe	$P_n =$	250	500	1000	2000	1-unit	$\text{coe } C =$	10.66	6.36	4.11	2.73	$\text{jC} =$	21	24	28	34	
		500	1000	2000	4000	2-units		7.34	4.48	3	2.05		23	26	31	38	
		1000	2000	4000	8000	4-units		5.54	3.46	2.38	1.67		25	28	34	42	
		2000	4000	8000	16000	8-units		4.54	2.88	2.03	1.45		26	30	36	44	
Optimal driver energy (MJ) :		$\text{Ed}_{C_{i,k}} = \text{Ed}_{\text{jC}_{i,k}}$				Optimal target gain:		$G_{C_{i,k}} = G(\text{Ed}_{C_{i,k}})$				Optimal target yield (MJ)		$Y_{C_{i,k}} = Y(\text{Ed}_{C_{i,k}})$			
$\text{Ed}_C =$		$\begin{bmatrix} 4 & 4.7 & 5.8 & 7.4 \\ 4.5 & 5.2 & 6.6 & 8.6 \\ 5 & 5.8 & 7.4 & 9.8 \\ 5.2 & 6.3 & 8 & 10.4 \end{bmatrix}$				$G_C =$		$\begin{bmatrix} 53 & 66 & 81 & 99 \\ 62 & 74 & 90 & 110 \\ 70 & 81 & 99 & 120 \\ 74 & 87 & 104 & 126 \end{bmatrix}$				$Y_C =$		$\begin{bmatrix} 213 & 314 & 467 & 733 \\ 279 & 388 & 594 & 941 \\ 351 & 467 & 733 & 1183 \\ 388 & 551 & 834 & 1319 \end{bmatrix}$			
Optimal rep rate (Hz/unit):		$\text{RRch}_{C_{i,k}} = \text{RRch}_{\text{dcjC}_{i,k,k}}$				Optimal thermal power MW/unit:		$\text{Pt}_{C_{i,k}} = \text{Pt}_{\text{dcjC}_{i,k,k}}$				Optimal recirc. power MWe/unit:		$\text{frec}_{C_{i,k}} = \text{frec}_{\text{dcjC}_{i,k,k}}$			
$\text{RRch}_C =$		$\begin{bmatrix} 2.1 & 2.7 & 3.5 & 4.3 \\ 1.5 & 2.1 & 2.7 & 3.3 \\ 1.2 & 1.7 & 2.1 & 2.6 \\ 1.1 & 1.5 & 1.9 & 2.3 \end{bmatrix}$				$\text{Pt}_C =$		$\begin{bmatrix} 526 & 1000 & 1927 & 3727 \\ 513 & 983 & 1895 & 3669 \\ 503 & 970 & 1869 & 3619 \\ 499 & 959 & 1855 & 3596 \end{bmatrix}$				$\text{frec}_C =$		$\begin{bmatrix} 0.142 & 0.106 & 0.082 & 0.065 \\ 0.125 & 0.096 & 0.074 & 0.058 \\ 0.114 & 0.089 & 0.068 & 0.053 \\ 0.11 & 0.083 & 0.064 & 0.051 \end{bmatrix}$			

CASE (C) SUMMARY—OPTIMAL DIRECT CAPITAL COSTS (M-9JS)

$$Cdr_{C_{1,k}} = Cdr1_{jC_{1,k},k}$$

$$Cdr_{C_{2,k}} = Cdr2_{jC_{2,k},k}$$

$$Cdr_{C_{3,k}} = Cdr4_{jC_{3,k},k}$$

$$Cdr_{C_{4,k}} = Cdr8_{jC_{4,k},k}$$

$$Cfc_{C_{1,k}} = Cfc1_{jC_{1,k},k}$$

$$Cfc_{C_{2,k}} = Cfc2_{jC_{2,k},k}$$

$$Cfc_{C_{3,k}} = Cfc4_{jC_{3,k},k}$$

$$Cfc_{C_{4,k}} = Cfc8_{jC_{4,k},k}$$

$$Csp_{C_{1,k}} = Csp1_{jC_{1,k},k}$$

$$Csp_{C_{2,k}} = Csp2_{jC_{2,k},k}$$

$$Csp_{C_{3,k}} = Csp4_{jC_{3,k},k}$$

$$Csp_{C_{4,k}} = Csp8_{jC_{4,k},k}$$

Driver Group Costs

$$Cdr_C = \begin{bmatrix} 430 & 466 & 514 & 578 \\ 478 & 520 & 580 & 659 \\ 550 & 601 & 676 & 770 \\ 660 & 729 & 820 & 934 \end{bmatrix}$$

Fusion Chamber Group Costs

$$Cfc_C = \begin{bmatrix} 277 & 338 & 483 & 681 \\ 446 & 543 & 780 & 1104 \\ 771 & 936 & 1352 & 1921 \\ 1399 & 1691 & 2454 & 3494 \end{bmatrix}$$

Steam Plant Group Costs

$$Csp_C = \begin{bmatrix} 156 & 222 & 325 & 485 \\ 269 & 384 & 561 & 837 \\ 487 & 697 & 1017 & 1514 \\ 911 & 1301 & 1901 & 2832 \end{bmatrix}$$

$$Ctd_C = Cdr_C + Cfc_C + Csp_C$$

Total Direct Costs

$$Ctd_C = \begin{bmatrix} 863 & 1026 & 1321 & 1744 \\ 1192 & 1447 & 1922 & 2600 \\ 1807 & 2234 & 3045 & 4205 \\ 2970 & 3720 & 5175 & 7261 \end{bmatrix}$$

For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000$ MWe/unit --

$$\begin{matrix} \text{Total plant} \\ \text{net power} \\ \text{MWe} \end{matrix} \quad P_n = \begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix} \begin{matrix} 1\text{-unit} \\ 2\text{-units} \\ 4\text{-units} \\ 8\text{-units} \end{matrix}$$

Miscellaneous

Bypass Pump Power (total for plant)

$$Pbp_{C_{i,k}} = P_{bpb} (RRch_{dcjC_{i,k},k}) \cdot Nu_i$$

$$Pbp_C = \begin{bmatrix} 12 & 13 & 15 & 18 \\ 21 & 24 & 26 & 30 \\ 41 & 45 & 48 & 52 \\ 80 & 85 & 91 & 99 \end{bmatrix}$$

Driver Power (total for plant)

$$PHI_{C_{i,k}} = P_{HI} (Ed_{jC_{i,k},k}, RRch_{dcjC_{i,k},k}) \cdot Nu_i$$

$$PHI_C = \begin{bmatrix} 23 & 35 & 52 & 78 \\ 38 & 59 & 89 & 133 \\ 65 & 105 & 156 & 231 \\ 121 & 188 & 287 & 431 \end{bmatrix}$$

Target Factory Direct Costs

$$CTF_{C_{i,k}} = C_{TFE} (RRch_{dcjC_{i,k},k}, Nu_i, Pt_{dcjC_{i,k},k}, \eta_{ccjC_{i,k},k})$$

$$CTF_C = \begin{bmatrix} 29 & 35 & 42 & 50 \\ 37 & 46 & 56 & 68 \\ 49 & 64 & 77 & 94 \\ 71 & 90 & 112 & 140 \end{bmatrix}$$

Fusion Chamber Direct Costs

$$CFC_{C_{i,k}} = C_{FC} (Nu_i, Pt_{dcjC_{i,k},k}, Y(Ed_{jC_{i,k},k}))$$

$$CFC_C = \begin{bmatrix} 13 & 21 & 33 & 53 \\ 28 & 42 & 67 & 109 \\ 62 & 87 & 141 & 233 \\ 126 & 186 & 291 & 473 \end{bmatrix}$$

CASE (D) - ADVANCED TARGET GAINS WITH MHD+ STEAM COMBINED-CYCLE BOP

Case D One-unit plants

$$\begin{aligned} \text{coeD11}_j &= \text{coeD1}_{j,1} & \text{coeD}_{1,1} &= \min(\text{coeD11}) & \text{mD11}_j &= \text{until}(0.999 \cdot \text{coeD11}_j - \text{coeD}_{1,1}, 1) & \text{jD}_{1,1} &= \text{last}(\text{mD11}) & 250 \text{ MWe/unit} \\ \text{coeD12}_j &= \text{coeD1}_{j,2} & \text{coeD}_{1,2} &= \min(\text{coeD12}) & \text{mD12}_j &= \text{until}(0.999 \cdot \text{coeD12}_j - \text{coeD}_{1,2}, 1) & \text{jD}_{1,2} &= \text{last}(\text{mD12}) & 500 \text{ MWe/unit} \\ \text{coeD13}_j &= \text{coeD1}_{j,3} & \text{coeD}_{1,3} &= \min(\text{coeD13}) & \text{mD13}_j &= \text{until}(0.999 \cdot \text{coeD13}_j - \text{coeD}_{1,3}, 1) & \text{jD}_{1,3} &= \text{last}(\text{mD13}) & 1000 \text{ MWe/unit} \\ \text{coeD14}_j &= \text{coeD1}_{j,4} & \text{coeD}_{1,4} &= \min(\text{coeD14}) & \text{mD14}_j &= \text{until}(0.999 \cdot \text{coeD14}_j - \text{coeD}_{1,4}, 1) & \text{jD}_{1,4} &= \text{last}(\text{mD14}) & 2000 \text{ MWe/unit} \end{aligned}$$

Case D Two-unit plants

$$\begin{aligned} \text{coeD21}_j &= \text{coeD2}_{j,1} & \text{coeD}_{2,1} &= \min(\text{coeD21}) & \text{mD21}_j &= \text{until}(0.999 \cdot \text{coeD21}_j - \text{coeD}_{2,1}, 1) & \text{jD}_{2,1} &= \text{last}(\text{mD21}) & 250 \text{ MWe/unit} \\ \text{coeD22}_j &= \text{coeD2}_{j,2} & \text{coeD}_{2,2} &= \min(\text{coeD22}) & \text{mD22}_j &= \text{until}(0.999 \cdot \text{coeD22}_j - \text{coeD}_{2,2}, 1) & \text{jD}_{2,2} &= \text{last}(\text{mD22}) & 500 \text{ MWe/unit} \\ \text{coeD23}_j &= \text{coeD2}_{j,3} & \text{coeD}_{2,3} &= \min(\text{coeD23}) & \text{mD23}_j &= \text{until}(0.999 \cdot \text{coeD23}_j - \text{coeD}_{2,3}, 1) & \text{jD}_{2,3} &= \text{last}(\text{mD23}) & 1000 \text{ MWe/unit} \\ \text{coeD24}_j &= \text{coeD2}_{j,4} & \text{coeD}_{2,4} &= \min(\text{coeD24}) & \text{mD24}_j &= \text{until}(0.999 \cdot \text{coeD24}_j - \text{coeD}_{2,4}, 1) & \text{jD}_{2,4} &= \text{last}(\text{mD24}) & 2000 \text{ MWe/unit} \end{aligned}$$

Case D Four-unit plants

$$\begin{aligned} \text{coeD41}_j &= \text{coeD4}_{j,1} & \text{coeD}_{3,1} &= \min(\text{coeD41}) & \text{mD41}_j &= \text{until}(0.999 \cdot \text{coeD41}_j - \text{coeD}_{3,1}, 1) & \text{jD}_{3,1} &= \text{last}(\text{mD41}) & 250 \text{ MWe/unit} \\ \text{coeD42}_j &= \text{coeD4}_{j,2} & \text{coeD}_{3,2} &= \min(\text{coeD42}) & \text{mD42}_j &= \text{until}(0.999 \cdot \text{coeD42}_j - \text{coeD}_{3,2}, 1) & \text{jD}_{3,2} &= \text{last}(\text{mD42}) & 500 \text{ MWe/unit} \\ \text{coeD43}_j &= \text{coeD4}_{j,3} & \text{coeD}_{3,3} &= \min(\text{coeD43}) & \text{mD43}_j &= \text{until}(0.999 \cdot \text{coeD43}_j - \text{coeD}_{3,3}, 1) & \text{jD}_{3,3} &= \text{last}(\text{mD43}) & 1000 \text{ MWe/unit} \\ \text{coeD44}_j &= \text{coeD4}_{j,4} & \text{coeD}_{3,4} &= \min(\text{coeD44}) & \text{mD44}_j &= \text{until}(0.999 \cdot \text{coeD44}_j - \text{coeD}_{3,4}, 1) & \text{jD}_{3,4} &= \text{last}(\text{mD44}) & 2000 \text{ MWe/unit} \end{aligned}$$

Case D Eight-unit plants

$$\begin{aligned} \text{coeD81}_j &= \text{coeD8}_{j,1} & \text{coeD}_{4,1} &= \min(\text{coeD81}) & \text{mD81}_j &= \text{until}(0.999 \cdot \text{coeD81}_j - \text{coeD}_{4,1}, 1) & \text{jD}_{4,1} &= \text{last}(\text{mD81}) & 250 \text{ MWe/unit} \\ \text{coeD82}_j &= \text{coeD8}_{j,2} & \text{coeD}_{4,2} &= \min(\text{coeD82}) & \text{mD82}_j &= \text{until}(0.999 \cdot \text{coeD82}_j - \text{coeD}_{4,2}, 1) & \text{jD}_{4,2} &= \text{last}(\text{mD82}) & 500 \text{ MWe/unit} \\ \text{coeD83}_j &= \text{coeD8}_{j,3} & \text{coeD}_{4,3} &= \min(\text{coeD83}) & \text{mD83}_j &= \text{until}(0.999 \cdot \text{coeD83}_j - \text{coeD}_{4,3}, 1) & \text{jD}_{4,3} &= \text{last}(\text{mD83}) & 1000 \text{ MWe/unit} \\ \text{coeD84}_j &= \text{coeD8}_{j,4} & \text{coeD}_{4,4} &= \min(\text{coeD84}) & \text{mD84}_j &= \text{until}(0.999 \cdot \text{coeD84}_j - \text{coeD}_{4,4}, 1) & \text{jD}_{4,4} &= \text{last}(\text{mD84}) & 2000 \text{ MWe/unit} \end{aligned}$$

CASE D Summary- Optimized results for performance parameters: $\text{coe}_D := \text{coeD}$

For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000 \text{ MWe/ unit}$					Optimal CoE, cents/kWehr	Optimal driver energy indic:											
Total plant net power MWe	$P_n =$	250	500	1000	2000	$\text{coe}_D =$	9.29	5.64	3.71	2.51	$\text{jD} =$	6	9	12	15		
		500	1000	2000	4000		6.6	4.08	2.77	1.92		8	10	13	17		
		1000	2000	4000	8000		5.13	3.23	2.25	1.6		9	11	15	19		
		2000	4000	8000	16000		4.29	2.74	1.95	1.4		10	12	15	20		
Optimal driver energy (MJ):		$\text{Ed}_{D,i,k} = \text{Ed}_{jD,i,k}$				Optimal target gain:		$G_{D,i,k} = G_a(\text{Ed}_{D,i,k})$		Optimal target yield (MJ)		$Y_{D,i,k} = Y_a(\text{Ed}_{D,i,k})$					
$\text{Ed}_D =$		1.1	1.5	2.1	2.7	$G_D =$		165	207	243	275	$Y_D =$		175	317	503	733
		1.4	1.7	2.3	3.1			193	219	254	295			265	374	574	911
		1.5	1.9	2.7	3.5			207	231	275	314			317	436	733	1109
		1.7	2.1	2.7	3.8			219	243	275	323			374	503	733	1216
Optimal rep rate (Hz/unit):		$\text{RRch}_{D,i,k} = \text{RRch}_{dcajD,i,k,k}$				Optimal thermal power MW/unit:		$\text{Pt}_{D,i,k} = \text{Pt}_{dcajD,i,k,k}$		Optimal recirc. power MWe/unit:		$\text{frec}_{D,i,k} = \text{frec}_{dcajD,i,k,k}$					
$\text{RRch}_C =$		2.1	2.7	3.5	4.3	$\text{Pt}_C =$		526	1000	1927	3727	$\text{frec}_C =$		0.142	0.106	0.082	0.065
		1.5	2.1	2.7	3.3			513	983	1895	3669			0.125	0.096	0.074	0.058
		1.2	1.7	2.1	2.6			503	970	1869	3619			0.114	0.089	0.068	0.053
		1.1	1.5	1.9	2.3			499	959	1855	3596			0.11	0.083	0.064	0.051

CASE (D) SUMMARY—OPTIMAL DIRECT CAPITAL COSTS (M-93\$)

$$Cdr_{D_{1,k}} = Cdr_{1jD_{1,k,k}}$$

$$Cfc_{D_{1,k}} = Cfc_{1jD_{1,k,k}}$$

$$Csp_{D_{1,k}} = Csp_{1jD_{1,k,k}}$$

$$Cdr_{D_{2,k}} = Cdr_{2jD_{2,k,k}}$$

$$Cfc_{D_{2,k}} = Cfc_{2jD_{2,k,k}}$$

$$Csp_{D_{2,k}} = Csp_{2jD_{2,k,k}}$$

$$Cdr_{D_{3,k}} = Cdr_{4jD_{3,k,k}}$$

$$Cfc_{D_{3,k}} = Cfc_{4jD_{3,k,k}}$$

$$Csp_{D_{3,k}} = Csp_{4jD_{3,k,k}}$$

$$Cdr_{D_{4,k}} = Cdr_{8jD_{4,k,k}}$$

$$Cfc_{D_{4,k}} = Cfc_{8jD_{4,k,k}}$$

$$Csp_{D_{4,k}} = Csp_{8jD_{4,k,k}}$$

Driver Group Costs

Fusion Chamber Group Costs

Steam Plant Group Costs

$$Cdr_D = \begin{bmatrix} 419 & 503 & 620 & 667 \\ 544 & 658 & 824 & 730 \\ 737 & 904 & 940 & 871 \\ 1049 & 1301 & 1351 & 1154 \end{bmatrix}$$

$$Cfc_D = \begin{bmatrix} 1299 & 1598 & 2352 & 2433 \\ 1656 & 2384 & 3551 & 2286 \\ 2630 & 3780 & 3474 & 3345 \\ 4380 & 6264 & 6334 & 5813 \end{bmatrix}$$

$$Csp_D = \begin{bmatrix} 239 & 318 & 451 & 654 \\ 407 & 552 & 783 & 1060 \\ 738 & 1001 & 1300 & 1872 \\ 1373 & 1866 & 2445 & 3477 \end{bmatrix}$$

$$Ctd_D = Cdr_D + Cfc_D + Csp_D$$

Total Direct Costs

$$Ctd_D = \begin{bmatrix} 1958 & 2419 & 3423 & 3754 \\ 2607 & 3593 & 5157 & 4075 \\ 4105 & 5685 & 5714 & 6088 \\ 6802 & 9431 & 10130 & 10444 \end{bmatrix}$$

For net powers $P_{eu} = 250 \quad 500 \quad 1000 \quad 2000 \text{ MWe/unit}$

$$\begin{matrix} \text{Total plant} \\ \text{net power} \\ \text{MWe} \end{matrix} \quad P_n = \begin{bmatrix} 250 & 500 & 1000 & 2000 \\ 500 & 1000 & 2000 & 4000 \\ 1000 & 2000 & 4000 & 8000 \\ 2000 & 4000 & 8000 & 16000 \end{bmatrix} \begin{matrix} 1\text{-unit} \\ 2\text{-units} \\ 4\text{-units} \\ 8\text{-units} \end{matrix}$$

Miscellaneous

Bypass Pump Power (total for plant)

$$Pbp_{D_{i,k}} = P_{bpb} (RRch_{dcajD_{i,k,k}}) \cdot Nu_i$$

$$Pbp_D = \begin{bmatrix} 13 & 13 & 14 & 18 \\ 22 & 24 & 27 & 30 \\ 41 & 45 & 48 & 53 \\ 80 & 87 & 95 & 102 \end{bmatrix}$$

Driver Power (total for plant)

$$PHI_{D_{i,k}} = P_{HI} (Ed_{jD_{i,k,k}}, RRch_{dcajD_{i,k,k}}) \cdot Nu_i$$

$$PHI_D = \begin{bmatrix} 10 & 14 & 22 & 35 \\ 16 & 26 & 41 & 63 \\ 29 & 48 & 71 & 114 \\ 53 & 88 & 142 & 216 \end{bmatrix}$$

Target Factory Direct Costs

$$CTF_{D_{i,k}} = C_{TFE} (RRch_{dcajD_{i,k,k}}, Nu_i, Pt_{dcajD_{i,k,k}}, \eta_{ccjC_{i,k}}) CFC_{D_{i,k}} = C_{FC} (Nu_i, Pt_{dcajD_{i,k,k}}, Ya(Ed_{jD_{i,k,k}}))$$

$$CTF_D = \begin{bmatrix} 32 & 34 & 40 & 50 \\ 38 & 46 & 56 & 68 \\ 51 & 65 & 76 & 96 \\ 72 & 94 & 119 & 145 \end{bmatrix}$$

Fusion Chamber Direct Costs

$$CFC_D = \begin{bmatrix} 12 & 21 & 34 & 53 \\ 27 & 40 & 65 & 106 \\ 56 & 82 & 140 & 222 \\ 121 & 172 & 264 & 445 \end{bmatrix}$$

**DATE
FILMED**

8/25/94

END