Helical Fusion Power Plant Economics Studies

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Physics-Engineering-Cost (PEC) Code

Purpose: Compare COE from tokamaks, heliotrons, and modular stellarators.

Improvements

- data from 3 blanket-shield designs
- new cost schedule (based on the ARIES)
- more recent unit costs
- improved algorithms

COE variations with plasma and engineering parameters.

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PEC Code

Assumes R_p/a_p, β, T_o, P_e

Calculates plasma parameters and power balance

Adjusts R_p to match desired P_e

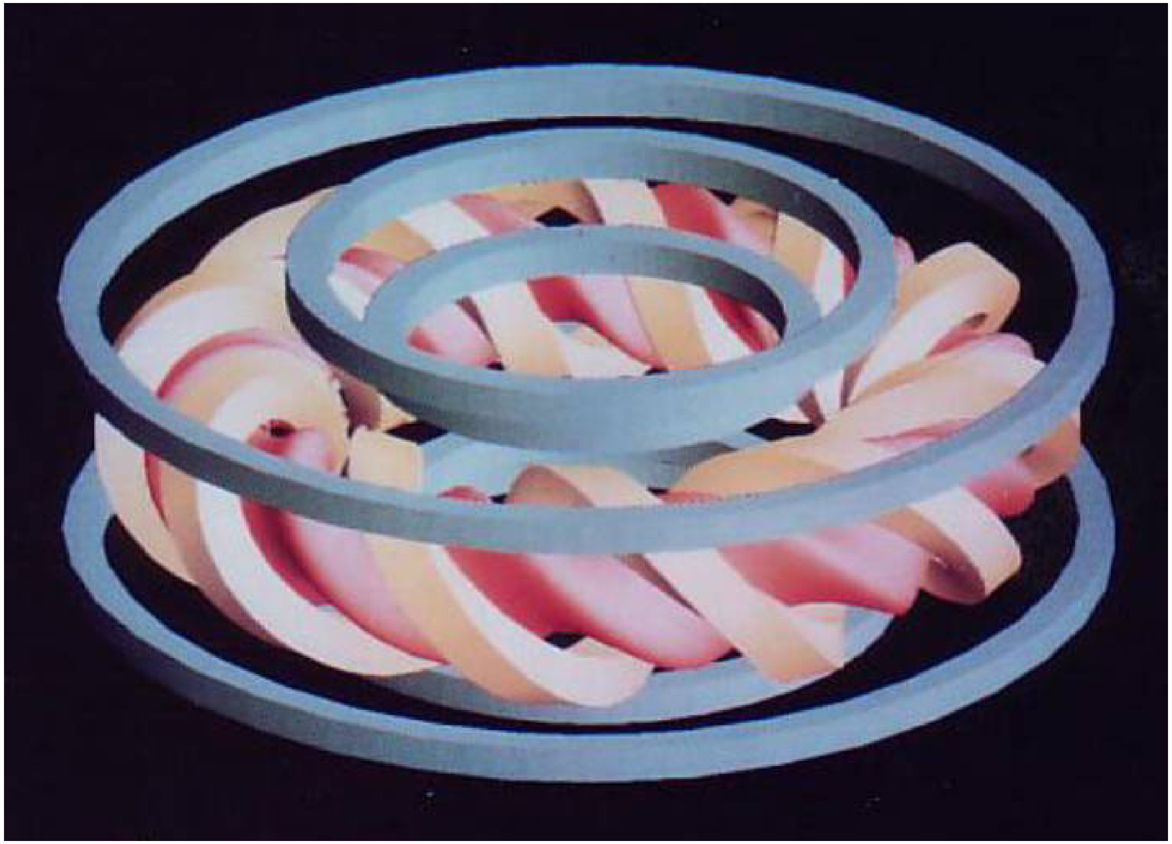
Masses & unit costs ($/kg) → capital cost → COE

Does not calculate

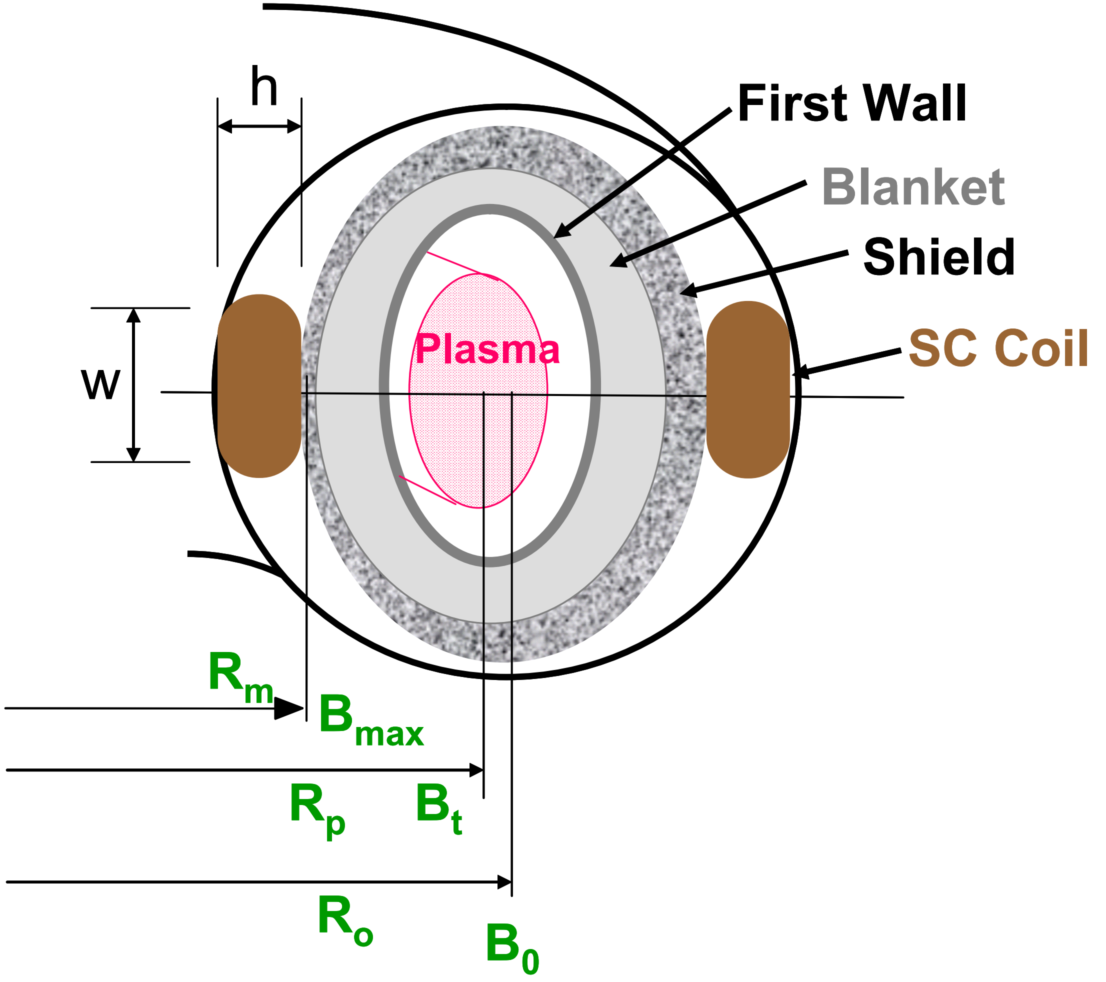
- Magnet coil details
- Plasma equilibrium, stability, and transport
- Structural masses
- Divertor details.

These are calculated elsewhere and input to the code.

Heliotron Coils l = 2, m = 10



Heliotron Reactor Model



Toroidal Magnetic Field in Plasma

l =2 stellarators

$$B_o/B_{max} = 0.476\,(80S_{coil}/R_o)^{0.4}\ (m/10)^{0.82}\,(1.2/\gamma_c)^{0.05}$$

S_{coil} = coil cross sectional area, derived from results of detailed computations.

Large S_{coil} → coil current density < maximum.

Average Plasma Density

$$n_{av} = \beta B_t^2/(4\mu_o k T_{av}).$$

k = Boltzmann constant,

μ_o = permeability of free space,

B_t = toroidal magnetic field at plasma center

T_{av} = density-weighted average temperature

Cost of Electricity (COE)

$\mathrm{COE} = [C_{AC} + (C_{O\&M} + C_{SCR} + C_F)(1+y)^Y]/(8760 P_e\, f_{avail}) + C_{D\&D}$

C_{AC} = (fixed charge rate)(total capital cost), M$/year

$C_{O\&M}$ = operations & maintenance cost, M$/year

C_{SCR} = scheduled component replacement cost, M$/year

C_F = annual fuel costs, M$/year

y = annual escalation rate

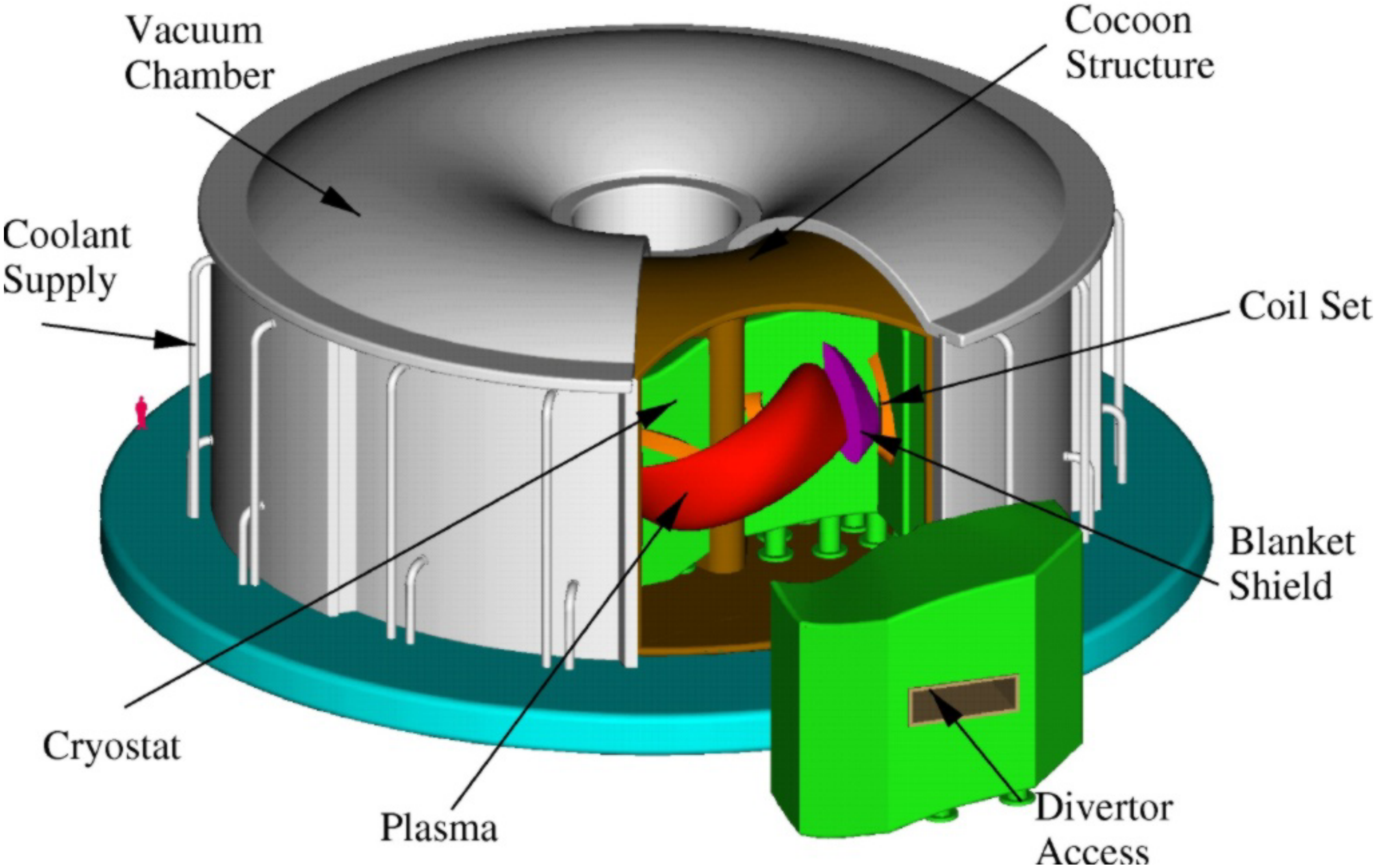
Y = construction period, assumed to be 6 years

P_e = net electrical power output, MWe

f_{avail} = plant availability factor

$C_{D\&D}$ = decontamination & decommissioning, mill/kWh.

SPPS Fusion Power Core System



PEC Modelling of ARIES-SPPS

COE, Mill/kWh	**PEC est.**	**SPPS**
Capital cost	67.27	63.02
Operation cost	8.89	9.16
Fuel	0.03	0.03
Blanket replacement	1.58	1.9
Decontamination & Decommissioning	0.5	0.5
Total	78.3	74.6

Blanket-Shield Comparison

	Units	**RAF-Flibe**	**V-Li (SPPS)**	**SiC-PbLi**
Inboard FW/BL/SH/VS thickness	m	0.95	1.29	1.02
Inboard blanket+shield cost	M$/m^2	0.27	0.37	0.25
Outboard blanket+shield costs	M$/m^2	0.27	0.37	0.34
Coolant outlet Temperature	C	560	610	1100
Energy conversion Efficiency	%	40	46	59
		Thinnest; But lowest efficiency	Thickest & most expensive; but might be made thinner.	Highest efficiency; but expensive materials

ISS-95 and NLHD-D1 scalings

$$\tau_{iss} = 0.26\ P^{-0.59}\ n_e^{0.51}\ B^{0.83}\ R^{0.65}\ a^{2.21}\ \iota_{2/3}^{0.4}$$

$$\tau_{NLHD} = 0.269\ P^{-0.59}\ n_e^{0.52}\ B^{1.06}\ R^{0.64}\ a^{2.58}$$

P = input heating power (MW)

n_e =average electron density (10^{20} m^{-3})

B = vacuum magnetic field at plasma center (T)

R = plasma major radius (m)

a = average plasma minor radius (m)

$\iota_{2/3}$ = is an average rotational transform

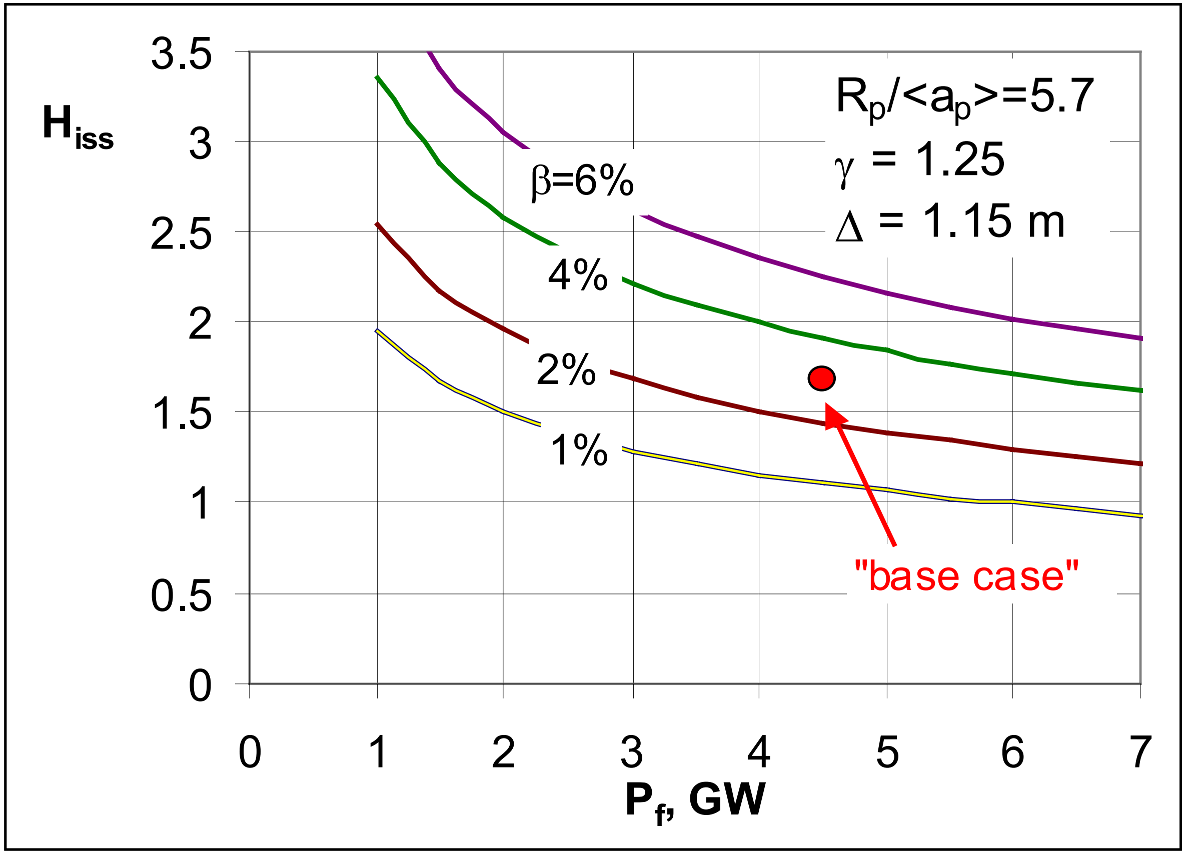
Energy Confinement H-factor

$$H_{iss} = \tau_E/\tau_{iss}$$

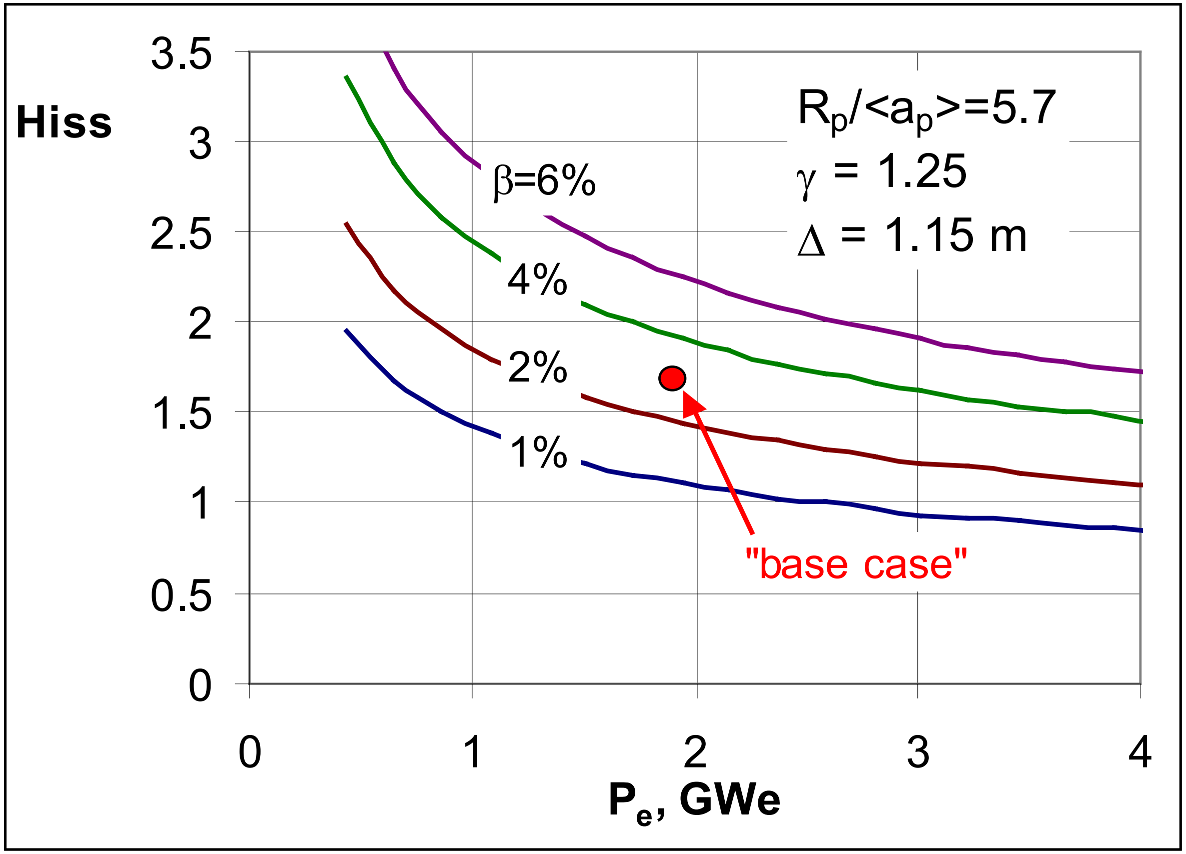
τ_E = observed or required energy confinement time.

H_{iss} = 1.5 achieved experimentally

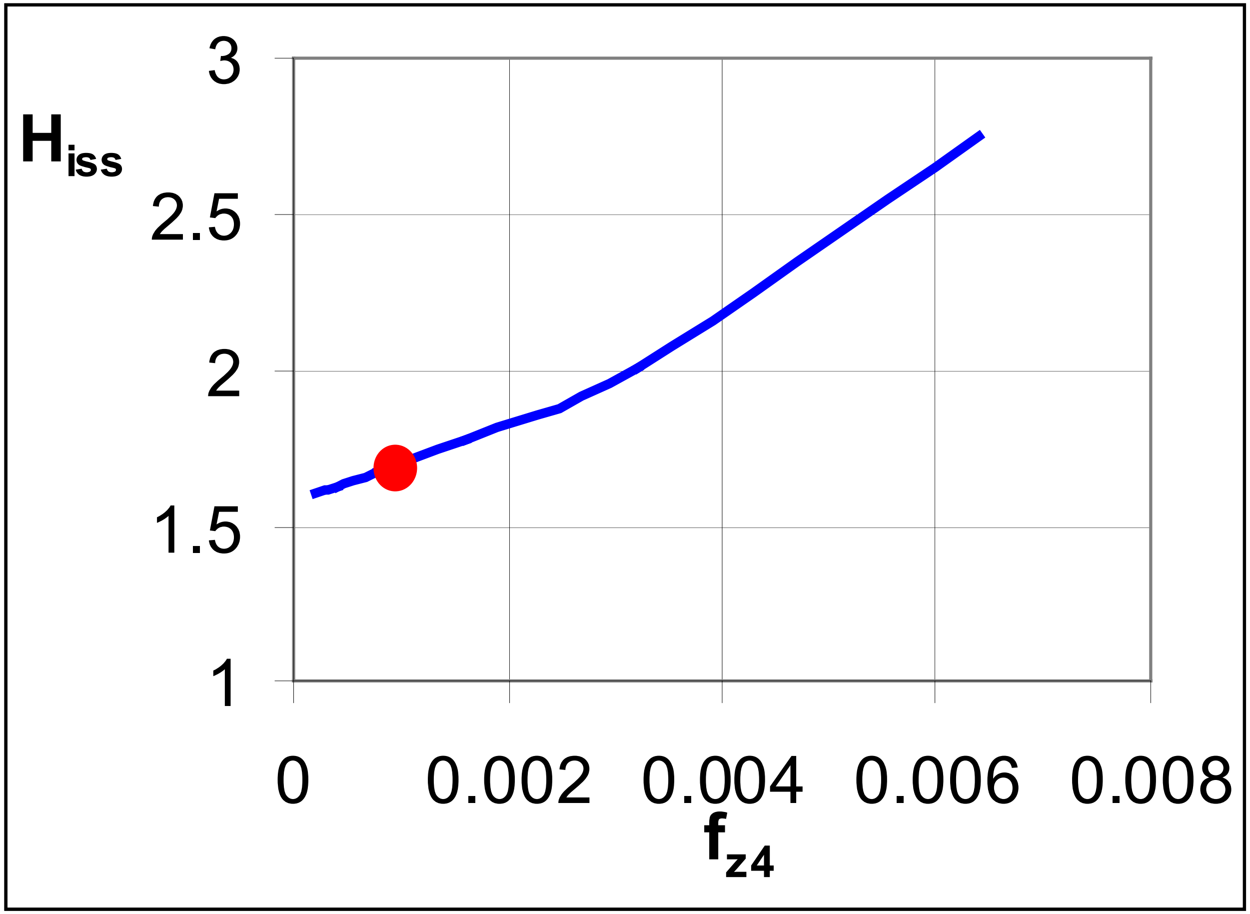
Required H_{iss} for Ignition



Required H_{iss} for Ignition



Required H_{iss} vs. Iron Impurity Fraction



Base Case Input Parameters

Average aspect ratio	$R_p/\langle a_p \rangle$	5.7
Coil pitch parameter	γ	1.25
Plasma average beta	β	3 %
Net electrical power output	P_e	1.94 GWe
Maximum field at coil	B_{max}	13
Coil width/depth	w/d	2
Coil maximum current density	J_{max}	30 MA/m^2
Attainable energy confinement relative to ISS-95:	H_{iss}	< 1.7
Energy conversion efficiency	η	40 %
M(poloidal coils) / M(helical coils)	f_{pol}	0.4
M(structure) / M(total coils)	f_{sup}	0.5
Central temperature	T_o	20 keV
Plasma elongation	κ	2.0

Direct Capital Cost Components

Magnet coil ~ 24% of the direct capital cost

Other components 4-6% each:

- Blanket
- Shield
- Heating systems
- Structure
- Vacuum system are 4-6% each

Cost reduction of an individual component does not have a large effect on COE

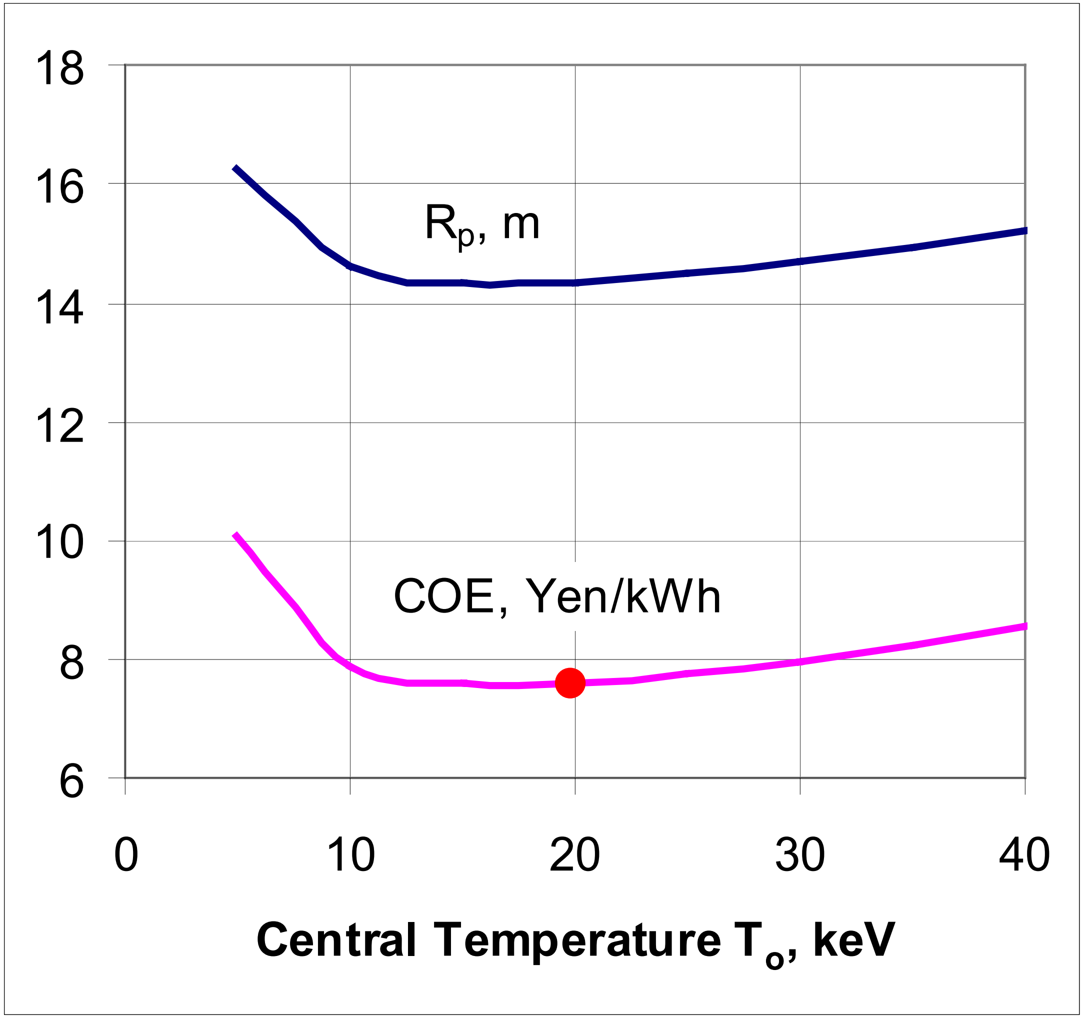
Base Case COE

COE capital cost (mil/kWh)	59.751
COE operations (mil/kWh)	7.875
COE fuel (mil/kWh)	0.019
COE replacement (mil/kWh)	3.387
COE Decon. & decom. (Mil/kWh)	0.612
Total COE (mil/kWh)	71.6

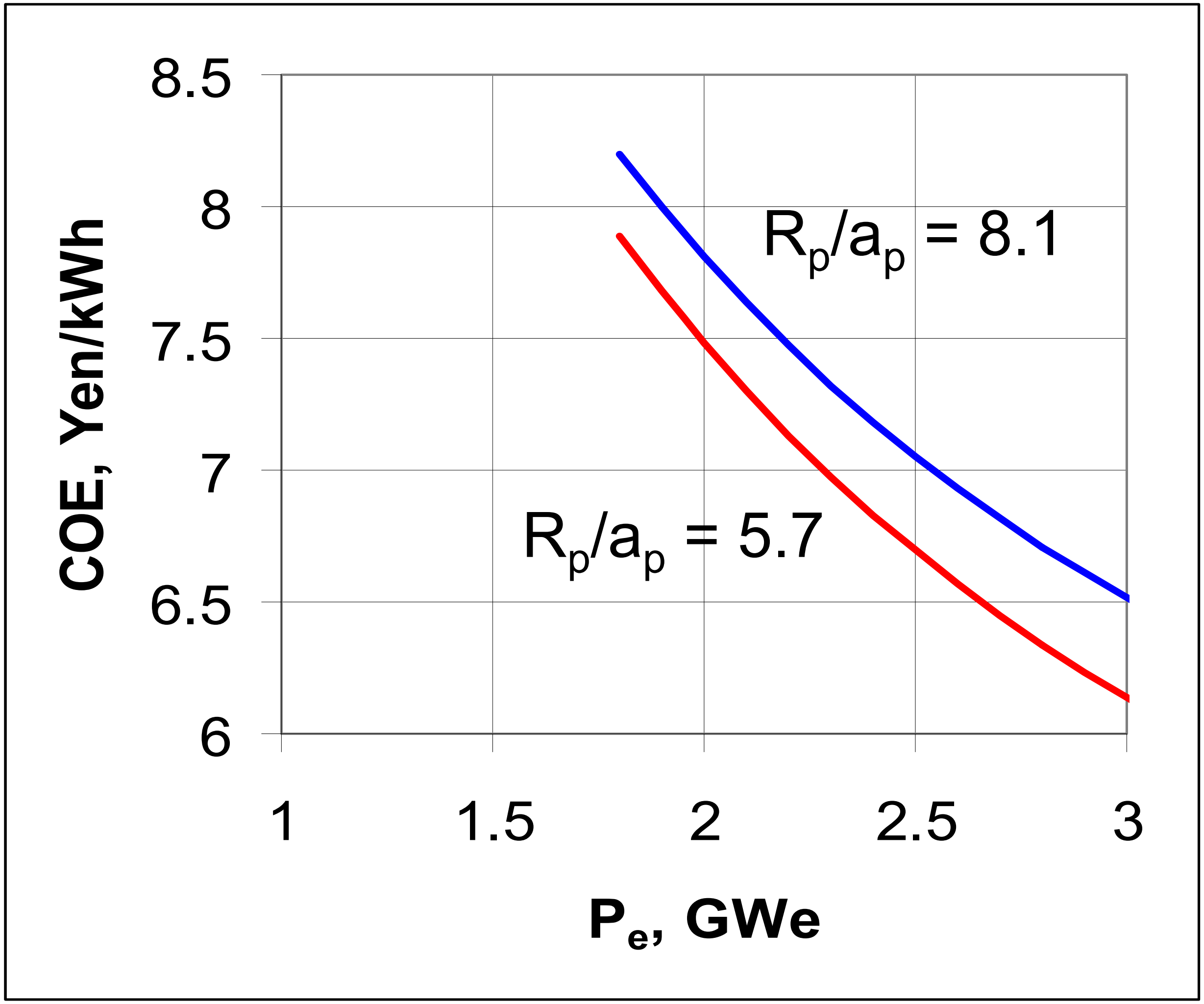
Base Case Results

Magnetic field ratio	B_o/B_{max}	0.48
Major radius of plasma	R_p	14.4 m
Fusion power	P_f	4.5 GWth
Neutron wall load		2.1 MW/m^2
Mass of helical coils	M_{hel}	6.2 kt
Mass of structure	M_{st}	4.3 kt
Mass of fusion island	M_{fi}	23.4 kt
Total capital cost	C_{cap}	7.9 G$
Relative capital cost	C_{cap}/P_e	4.1 $/W
Relative capital cost	C_{cap}/P_e	431. Yen/W
Mass power density	MPD	83. kWe/t
Cost of electricity	COE	72 mil/kWh
Cost of electricity	COE	7.6 Yen/kWh

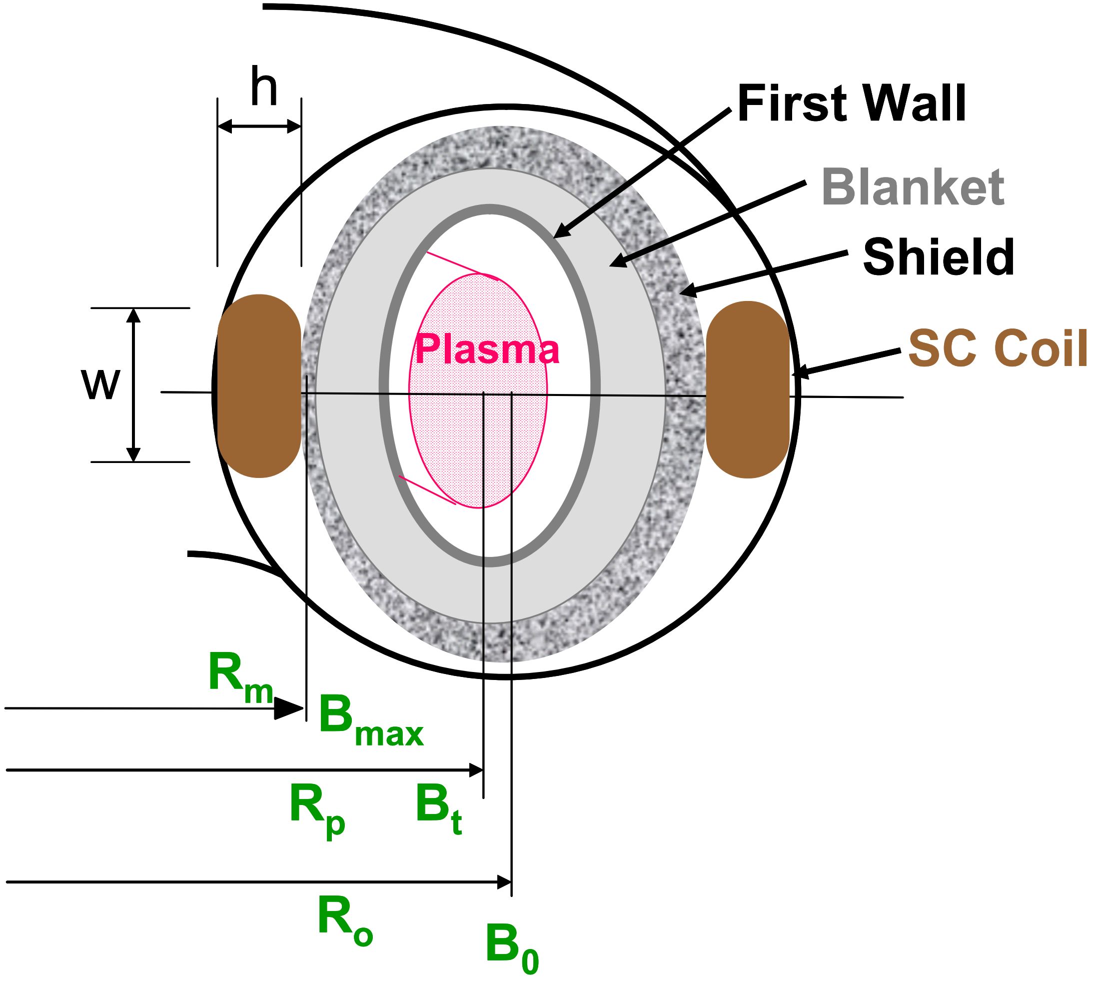
COE vs. Central Temperature



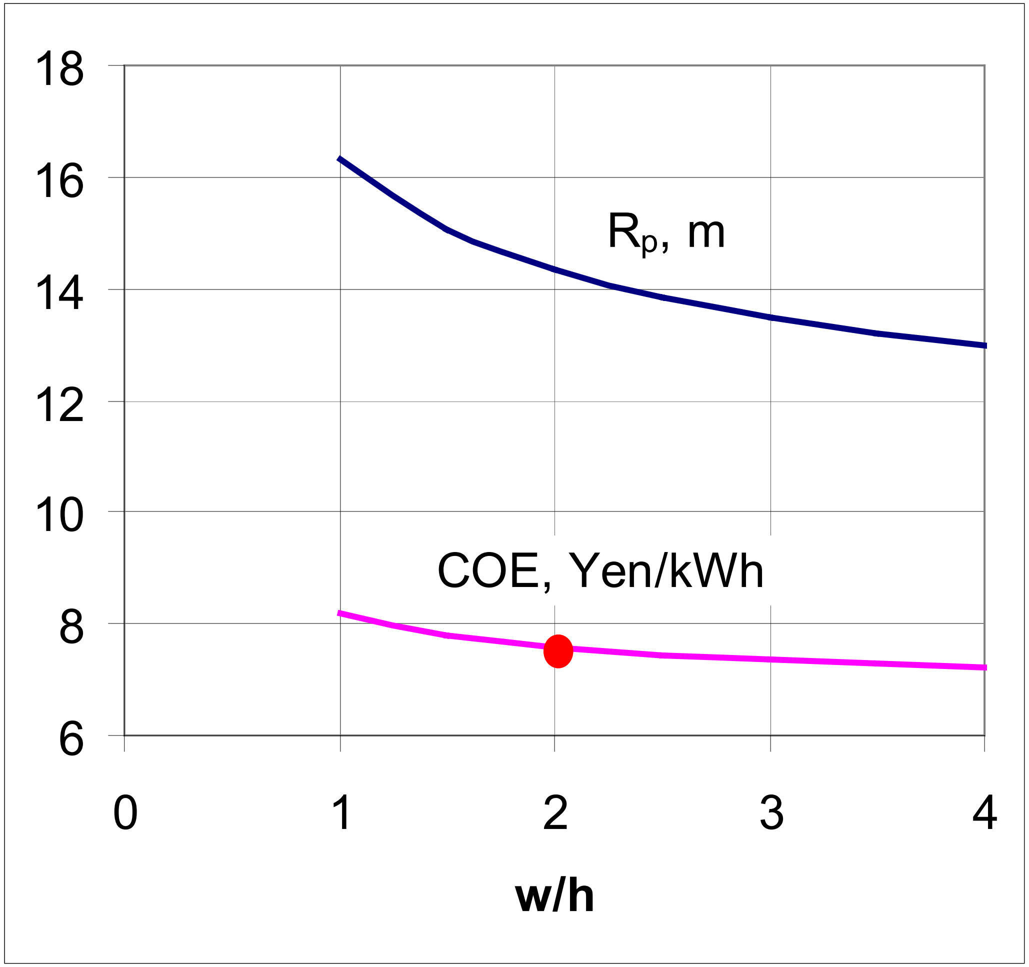
Comparison of Plasma Aspect Ratios



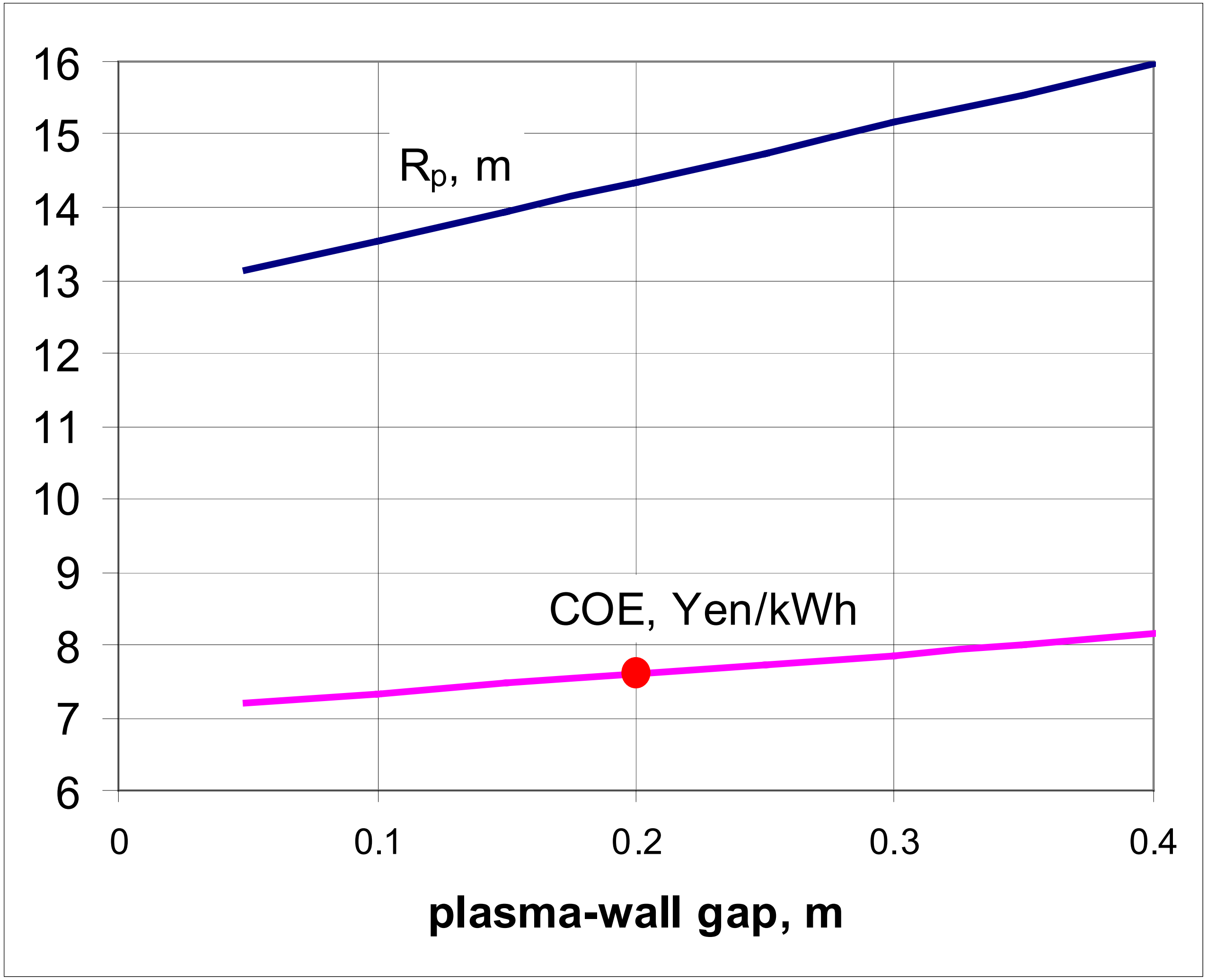
Heliotron Reactor Model



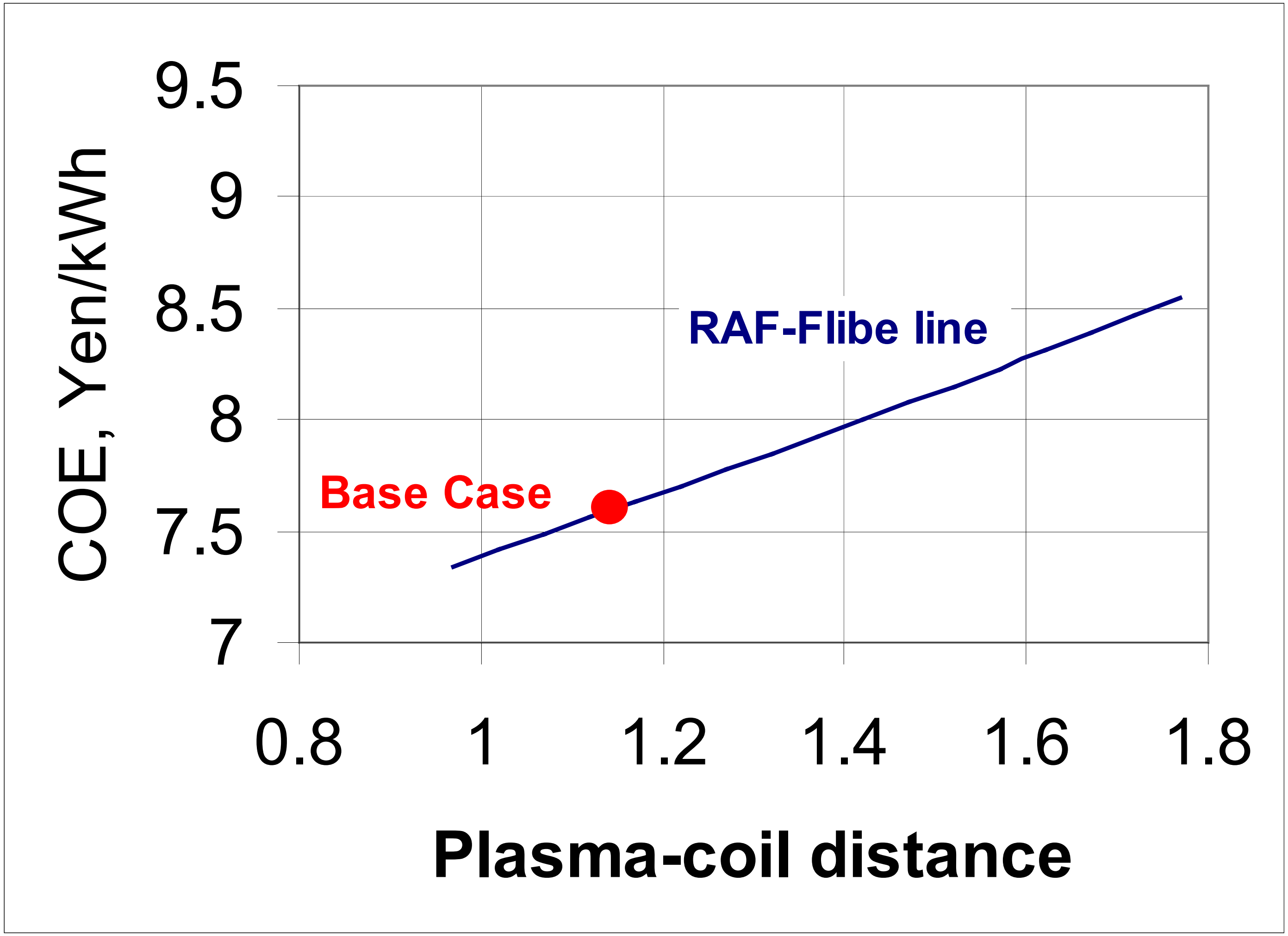
COE vs. Coil width/depth



COE vs. Plasma-Wall Gap Size



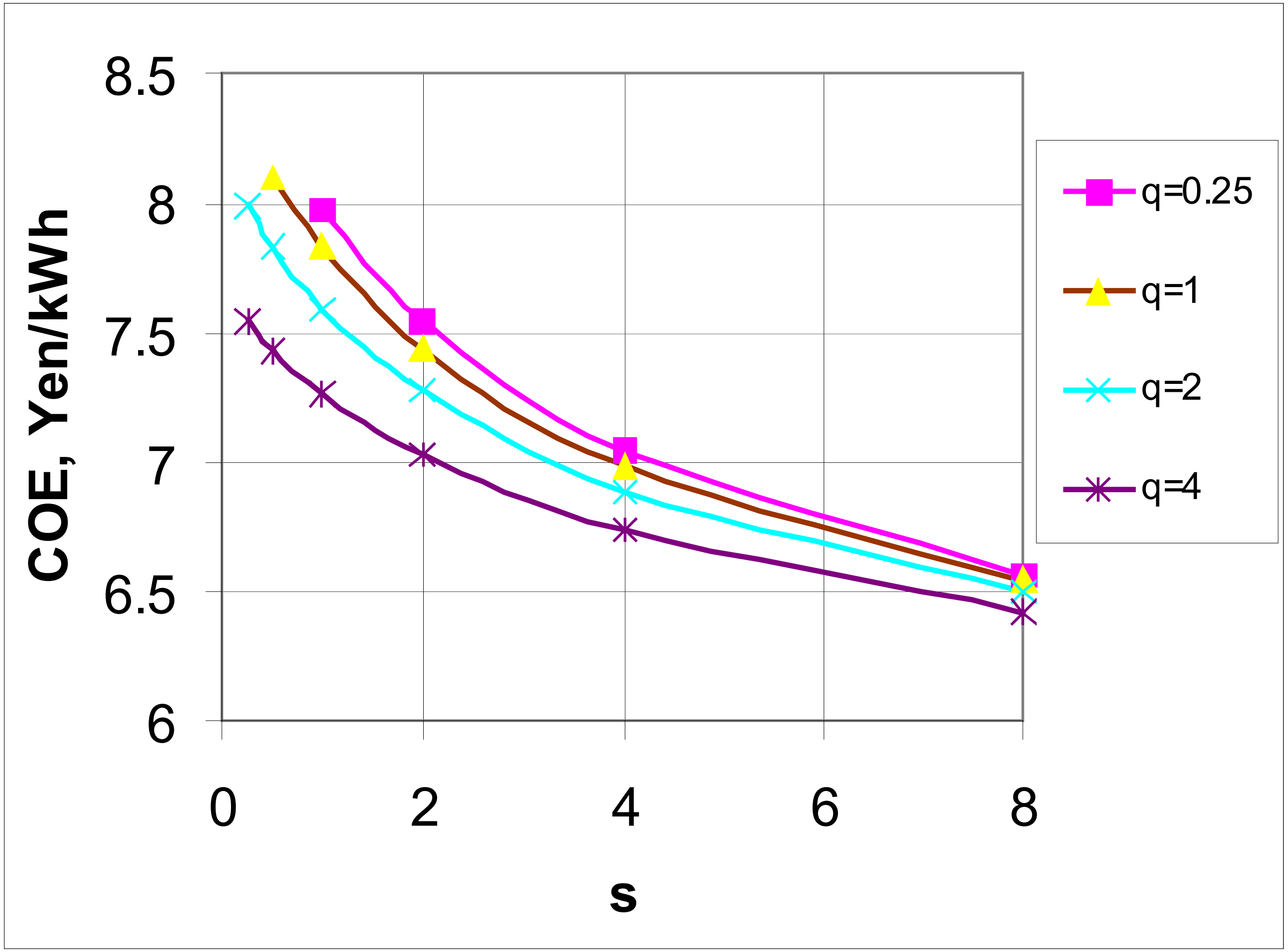
COE vs. Plasma-Coil Distance



COE vs. Profile Parameters

$$n(x)/\ n_o = (1\text{-}y_{ed})(1 - x^p)^q\ [d + (1\text{-}d)x^2] + y_{ed}$$

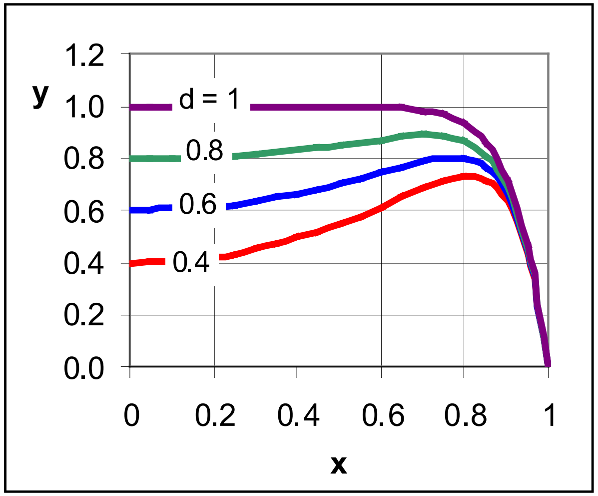
$$T(x)/\ T_o = (1\text{-}t_{ed})(1 - x^r)^s + t_{ed}$$

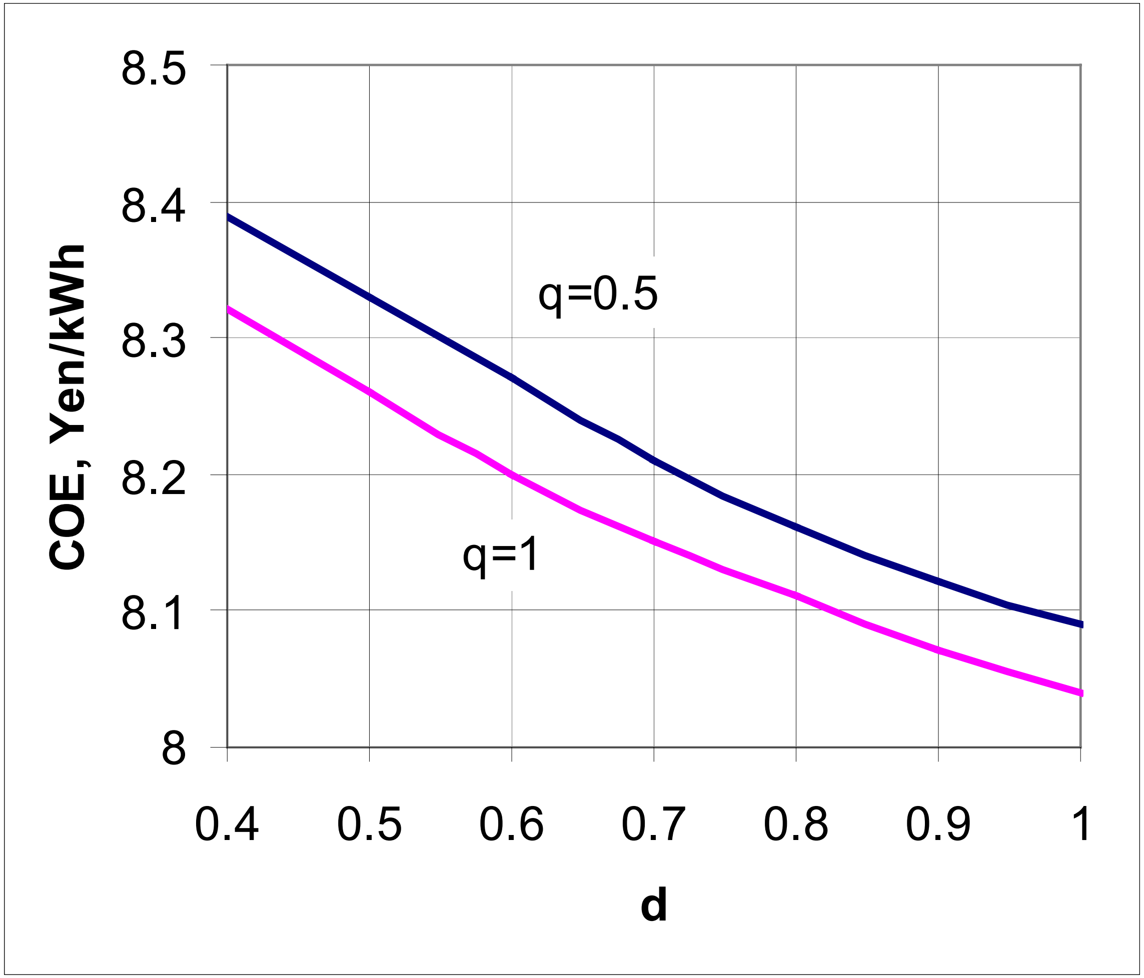


Effect of Hollow Density Profiles

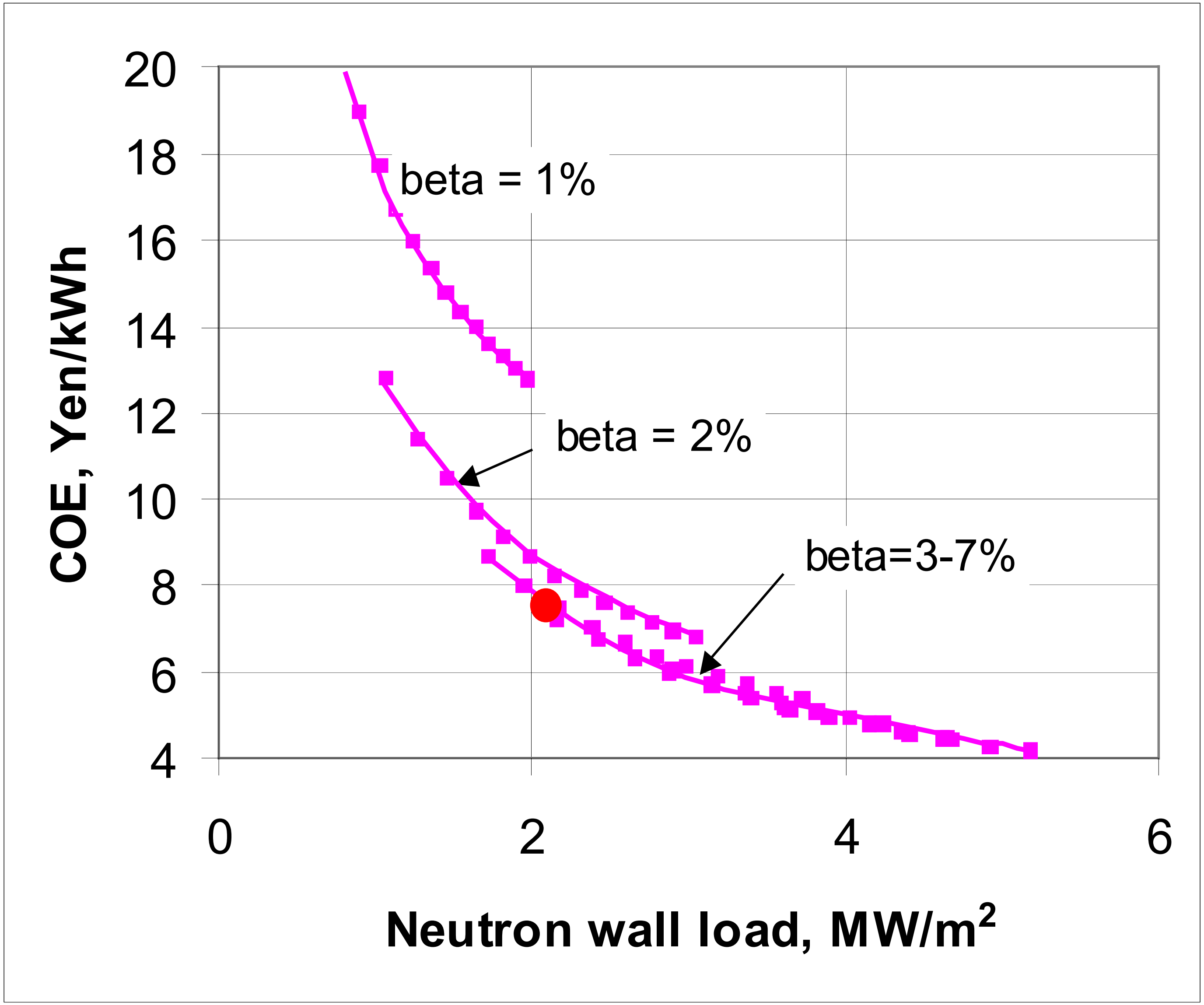
$$n(x)/n_o = (1-y_{ed})(1 - x^p)^q\,[d + (1-d)x^2] + y_{ed}$$

$$T(x)/T_o = (1-t_{ed})(1 - x^r)^s + t_{ed}$$

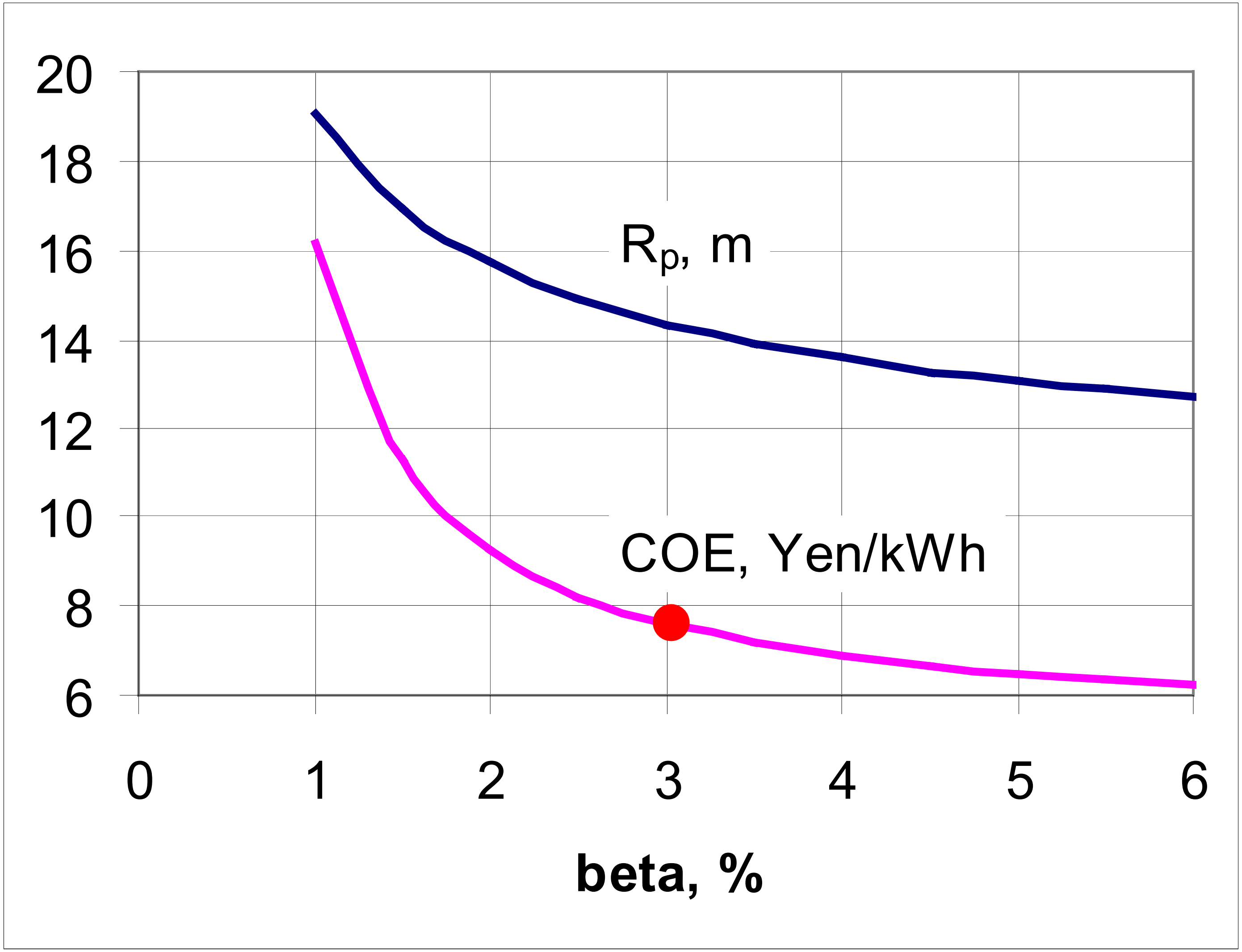




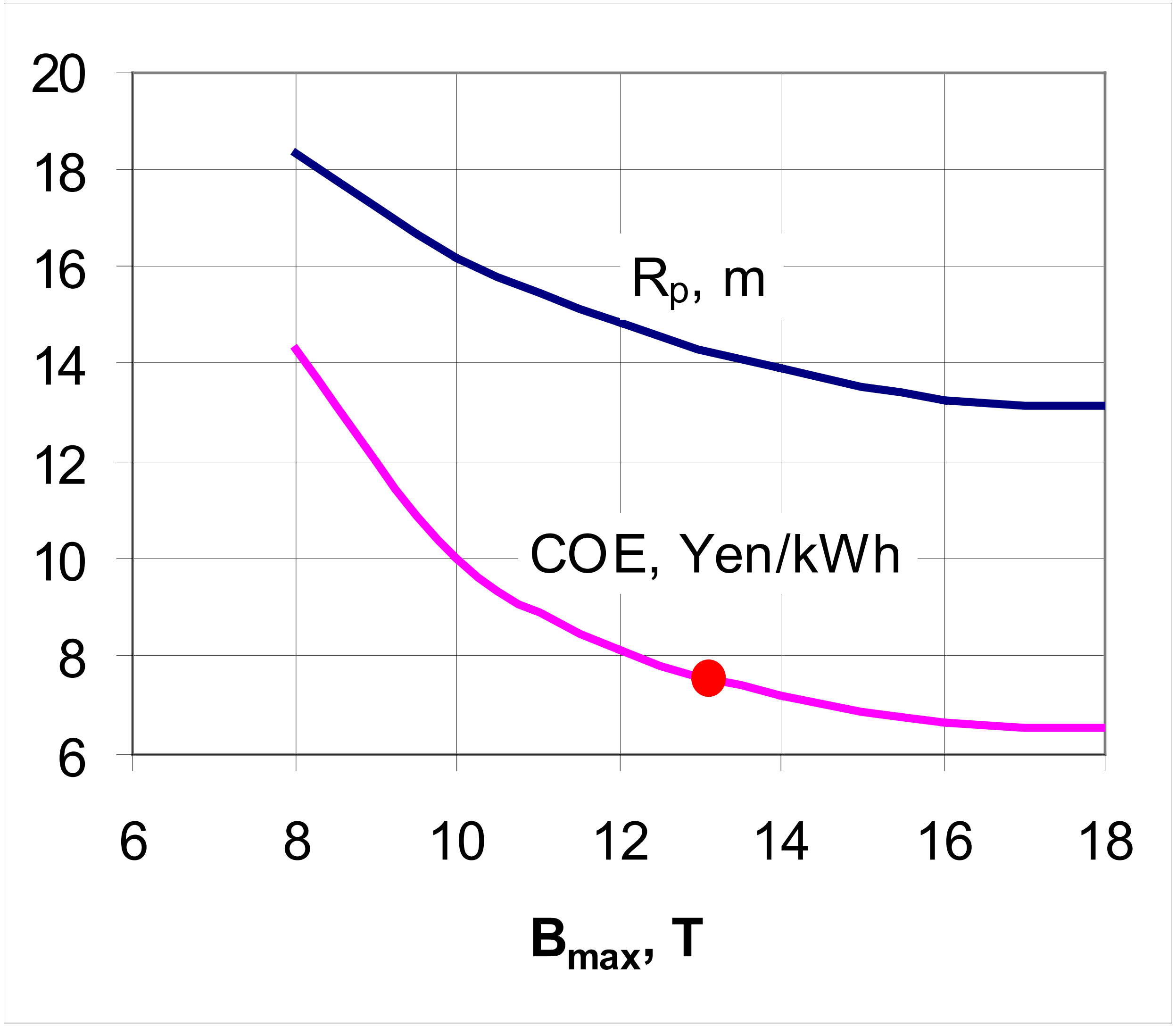
COE vs. Neutron Wall Load



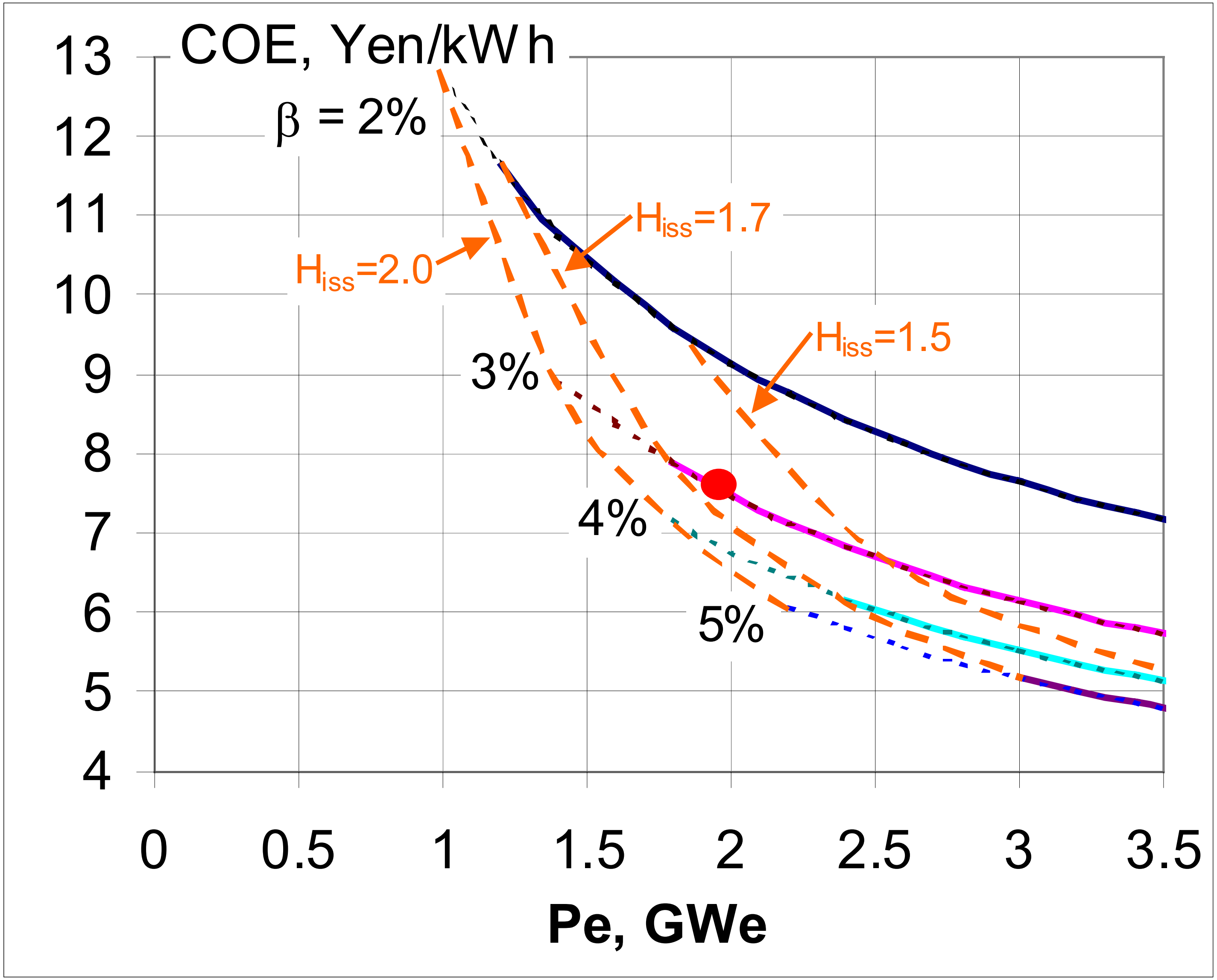
COE vs. beta



COE vs. B_{max}

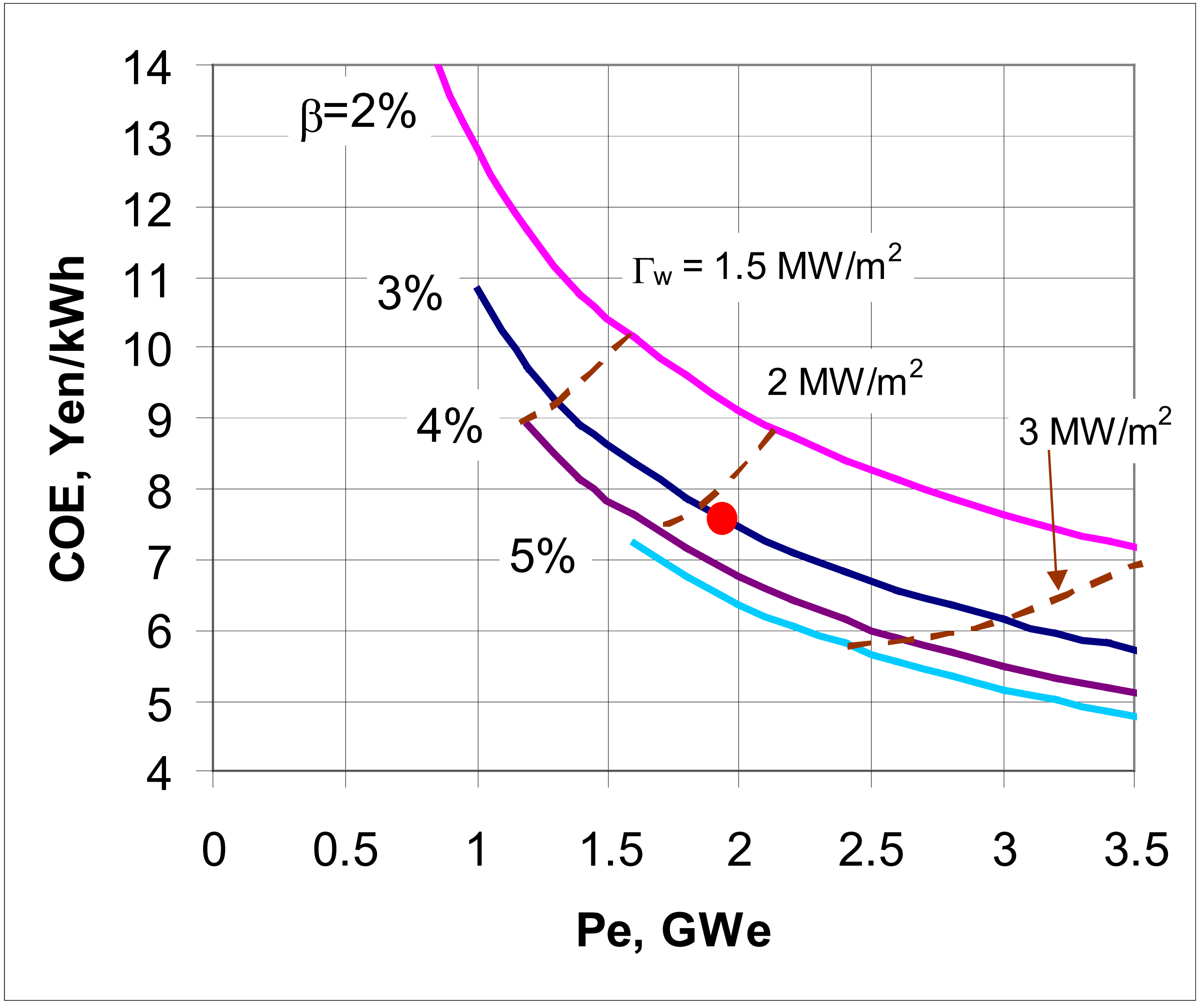


COE vs. Net Electrical Power



COE vs. Net Electrical Power

NLHD-D1 Scaling



Large Power Stations

8 hydroelectric plants > 5 GWe

Three Gorges Dam (China) = 18.2 GWe (2009)

9 nuclear power stations > 4 GWe.

New European PWR = 1.6 GWe, single reactor
(Limited by control and safety issues)

Heliotron Base Case = 1.94 GWe

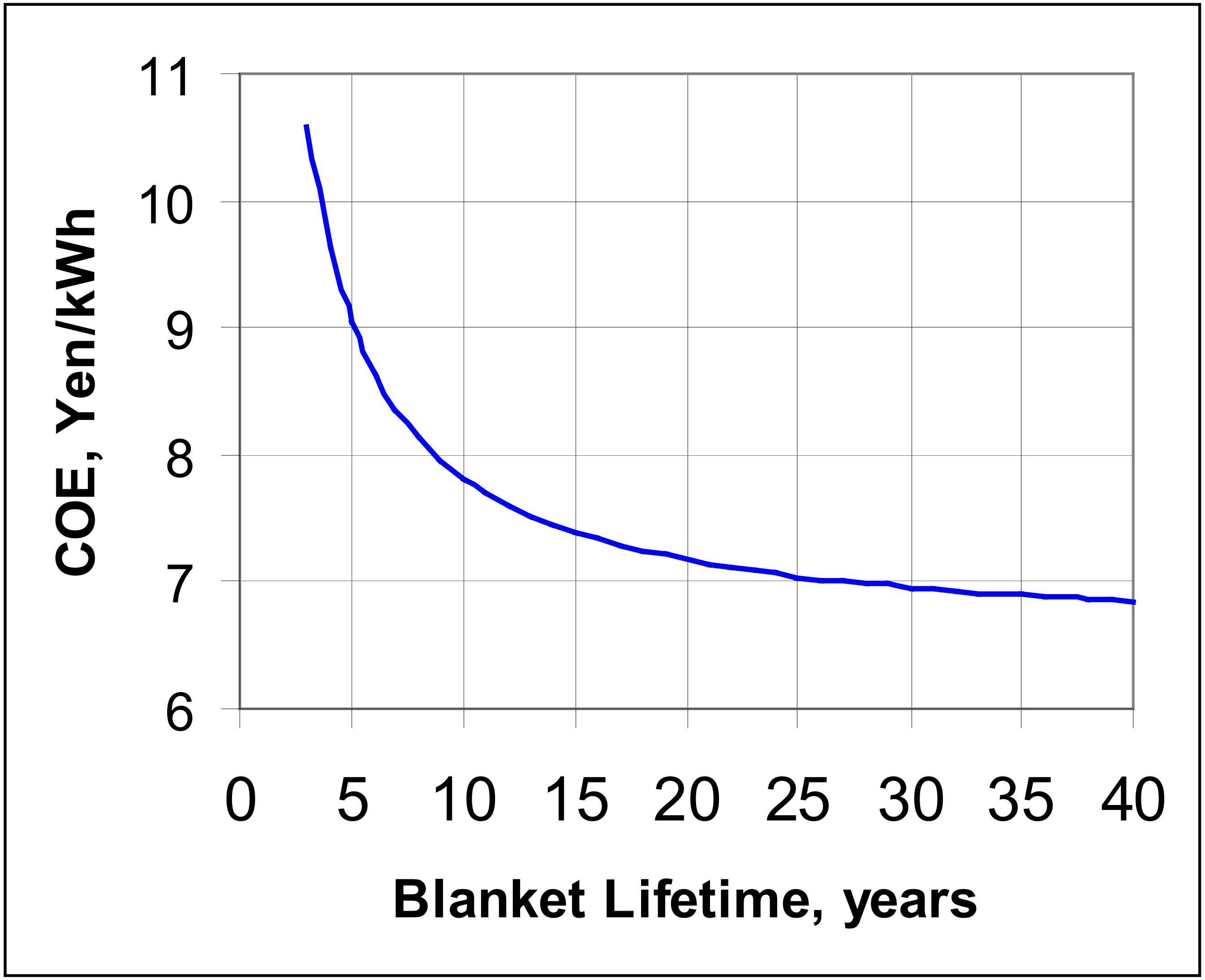
Grid Perturbation Avoidance

5 large reactors at one site, each
60% hydrogen, 40% electricity to grid.

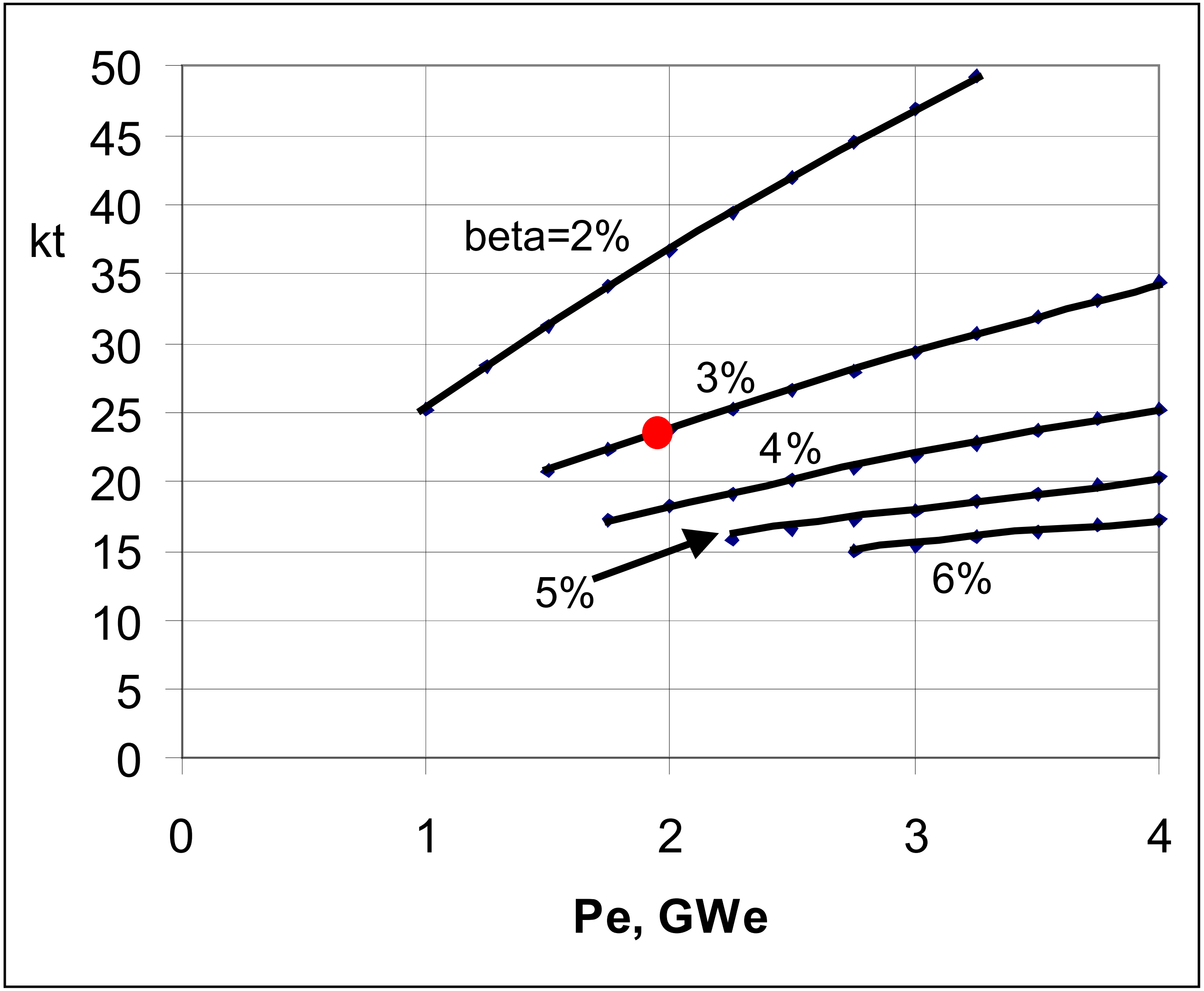
Outage of one reactor:
4 reactors, each
50% hydrogen, 50% electricity to grid.

Same electrical power to grid.

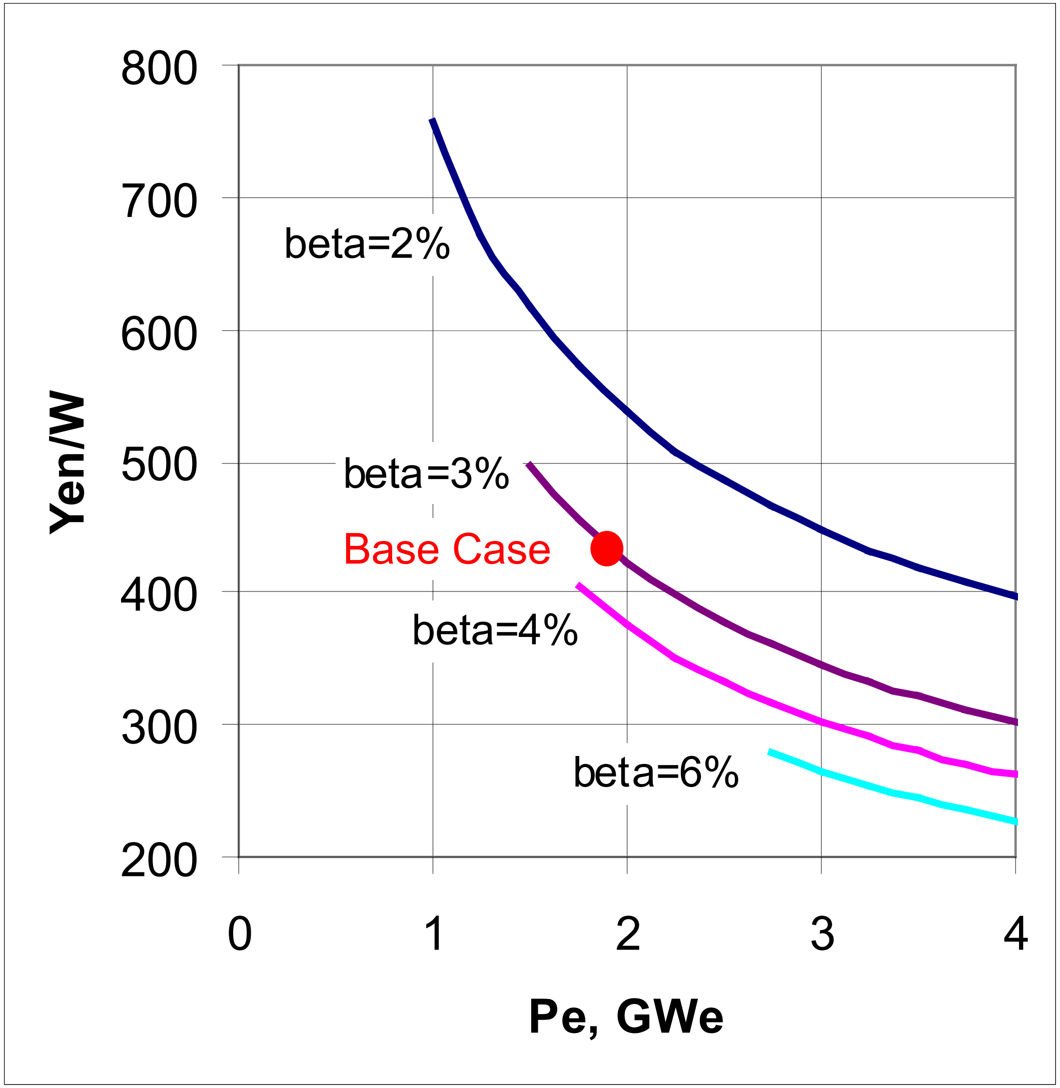
COE vs. Blanket Lifetime



Fusion Power Island Mass vs. P_e



Relative Capital Cost vs. P_e



Comparison with ITER

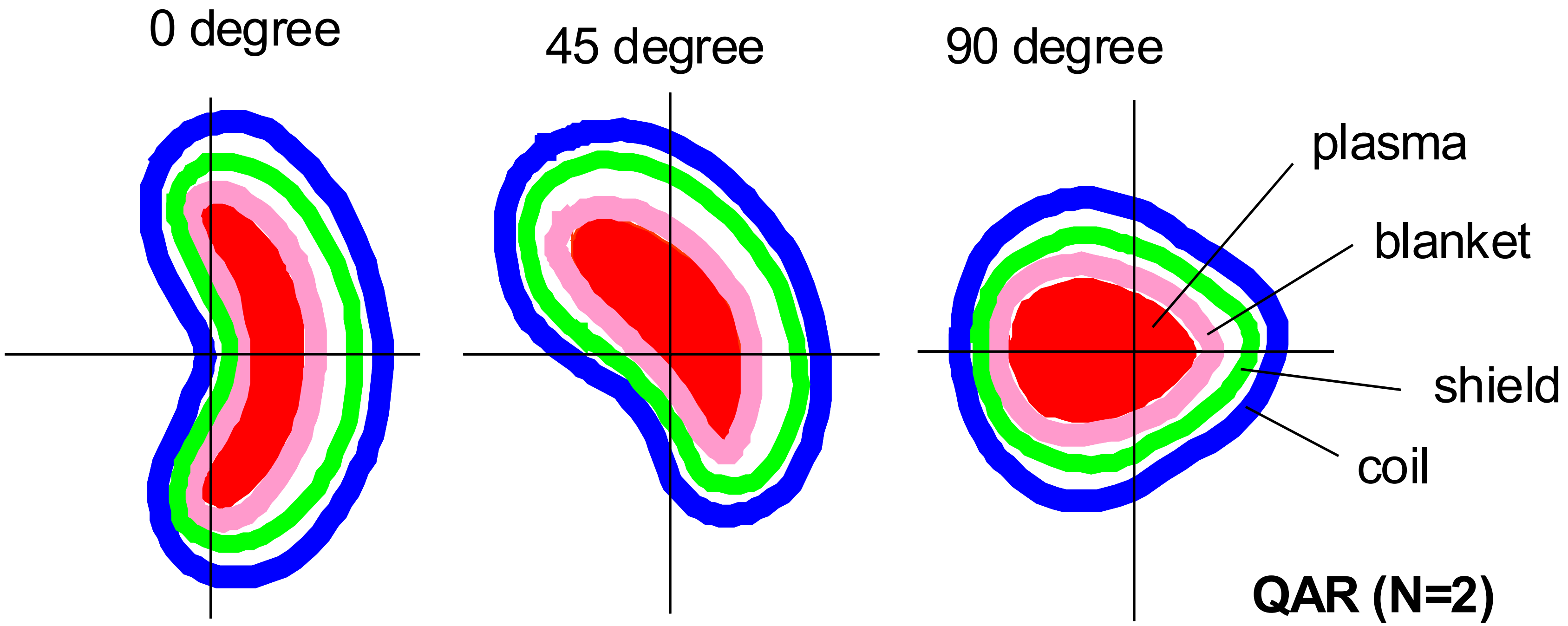
	Original ITER	Reduced ITER	Heliotron
TF coil, kt	14.8	6.6	
CS coil, kt	1.5	2.8	
PF coil, kt	3.8	2.6	
Total coil mass, kt	20.1	12.0	13.0
Total capital cost, G$	~ 10	~ 5	~ 8

COE in Japan

Source	**COE (Yen/kWh)**
Fission reactors	5.3
Coal	5.7
Natural gas	6.2
Oil	10.7
Pumped hydro storage	11.9
Heliotron “Base Case”	*7.6*

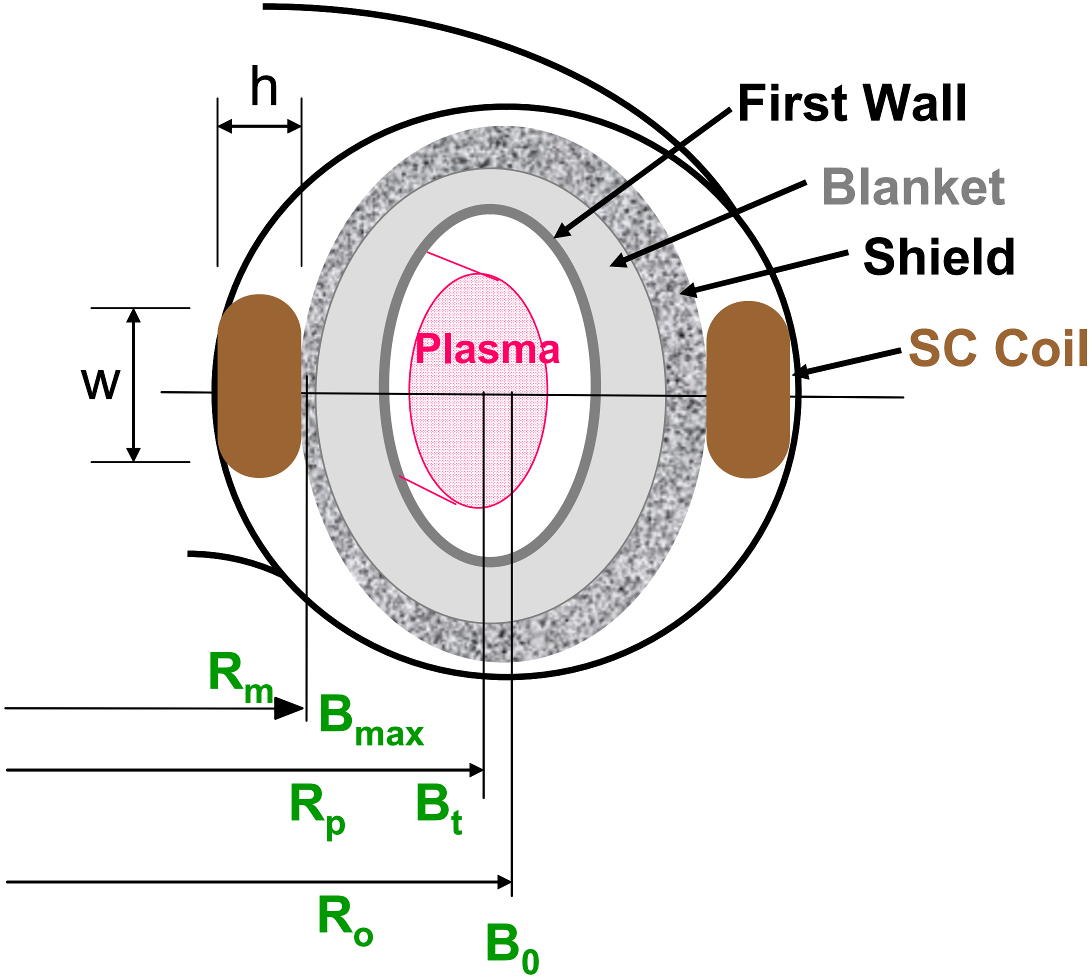
NLHD-scaling, β = 5% Heliotron: $\sim$ 5.2 Yen/kWh

CHS Modular Coil System



QAR (N=2)

Heliotron Reactor Model



Heliotrons & Modular Coil Stellarators

Heliotrons	**Modular coil stellarators**
Theoretical beta < 5%, 4% achieved	Potential beta > 5%, needs experimental verification.
Alpha confinement uncertain	Potentially good alpha confinement
Plasma aspect ratio restricted by γ_c to approximate range 5.5 -- 8.5.	Aspect ratio can vary over wide range. Low ratios may yield lower COE.
Natural helical divertor	Local divertors, space problem
Achieved Hiss ~ 1.5. NLHD-D1 scaling favorable	Achieved Hiss ~ 1.5.

Heliotrons & Modular Coil Stellarators

Heliotrons	**Modular coil stellarators**
Coil winding accuracy uncertain.	Coil winding & alignment to be demonstrated by W-7X.
Coil failure probably unfeasible to repair.	Failed coil or module could be replaced.
Alignment should last for the lifetime of the plant	Coils must be re-aligned after removal of a module
Lifetime blanket might be feasible.	Periodic replacement of blanket modules envisioned.
Large ports available for first wall replacement.	Port size generally smaller, depends on specific design.
Elliptical shape cross section permits close proximity of blanket and shield.	Odd shaped cross sections, more complex.

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Conclusions

Neutron wall load ~ 4 MW/m^2 desirable.

Increase B_{max}, β, or P_f.

COE vs. β is steep near $\beta = 3\%$, flattens out at $\beta > 6\%$,

Higher β → smaller a_p, lower τ_E

Strong economy of scale: High P_e → competitive COE

Many high-power stations already exist.

$R_p/\langle a_p \rangle = 5.7$ has lower COE than $R_p/\langle a_p \rangle = 8.1$

Hollow electron density profiles → higher COE

$B_{max} < 13$ T → higher COE

Estimated Component Costs

	M$	% direct cap. cost
20. Land & land rights	12.7	0.3
21. Structures & site facilities	450.3	11.1
22. Reactor plant equipment	2798.2	68.7
22.1 fusion reactor equipment	2090.2	51.3
22.1.1 FW/blanket/reflector	259.4	6.4
22.1.2 shield	254.3	6.2
22.1.3 magnets	956.7	23.5
22.2.4 current drive & heating	168.8	4.1
22.1.5 primary structure & support	169.3	4.2
22.1.6 vacuum systems	198.9	4.9
22.1.7 power supply	67.6	1.7
22.1.8 impurity control & divertor	15.2	0.4
22.1.10 ECRH breakdown system	4.9	0.1