TOROIDAL REACTOR DESIGNS AS A FUNCTION OF ASPECT RATIO

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ABSTRACT

This paper presents a 'common basis' systems study of superconducting (SC) and normal-conducting (NC) DT-burning fusion power and materials testing reactor designs. Figures-of-merit for power and materials-testing reactors are respectively projected cost-of-electricity (COE) and direct cost. A common 0-D plasma-modeling basis is used and the plasma geometry and engineering aspects of the SC and NC designs are treated in an equivalent manner that is consistent with the limitations of their respective magnet technologies and other design constraints. Aspect ratio A in the range $1.2 \leq A \leq 6$ and plasma elongation in the range $1 \leq k \leq 3$ is explored and a MHD stability (beta limit) physics basis is incorporated.

Results show that for power reactors the minimum COE is pointing towards A~2. The minimum is broader with higher κ. For test reactors with similar fusion power output, the direct cost for NC options is significantly lower that for SC options. An intermediate-A NC design with high elongation could provide scientific and testing data to support future SC or NC reactors. As an example, a NC design with A~2, κ=3 could produce 200 MW fusion power at 1.23 MW/m^2 average neutron wall loading at a total direct cost of about $643 M. This NC design with a fissile blanket at a blanket multiplication of 20 could also convert ~1270 kg of fission reactor waste per full power year.

INTRODUCTION

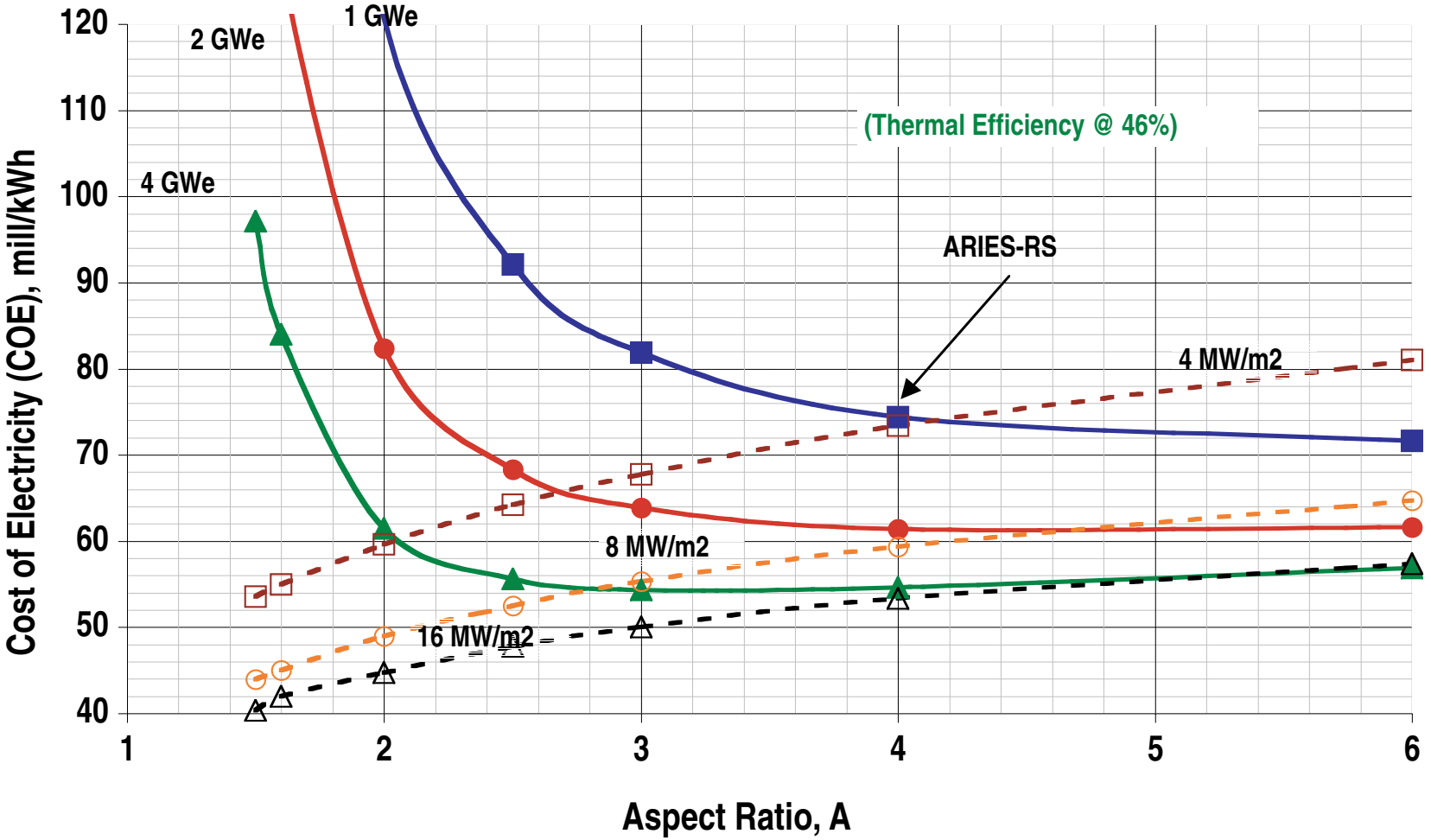
Do optimum power reactors operate at lower elongation "A", as indicated for NC design by earlier studies?

We evaluate the power and testing reactor regimes as a function of A and elongation κ = 1.5, 2 and 3.

- Fusion has the goal of producing economically and environmentally acceptable nuclear power.
- ITER with A~3 with conservative physics and engineering bases indicates relatively high development cost.
- A~4 (ARIES-RS, ARIES-AT... etc.) and A=1.6 (ARIES-ST) conceptual power reactors point designs have been studied.
- Our earlier systems paper studied the subject with $\kappa(A) = (0.277+9.129/A-5.748/A^2)$, and indicated NC designs have minimum COE around A = 1.4 to 1.6 and SC designs have minimum COE for A>3.

COE OF SUPERCONDUCTING COIL TOKAMAK REACTORS
(1999) CONSTANT BORE RADIUS

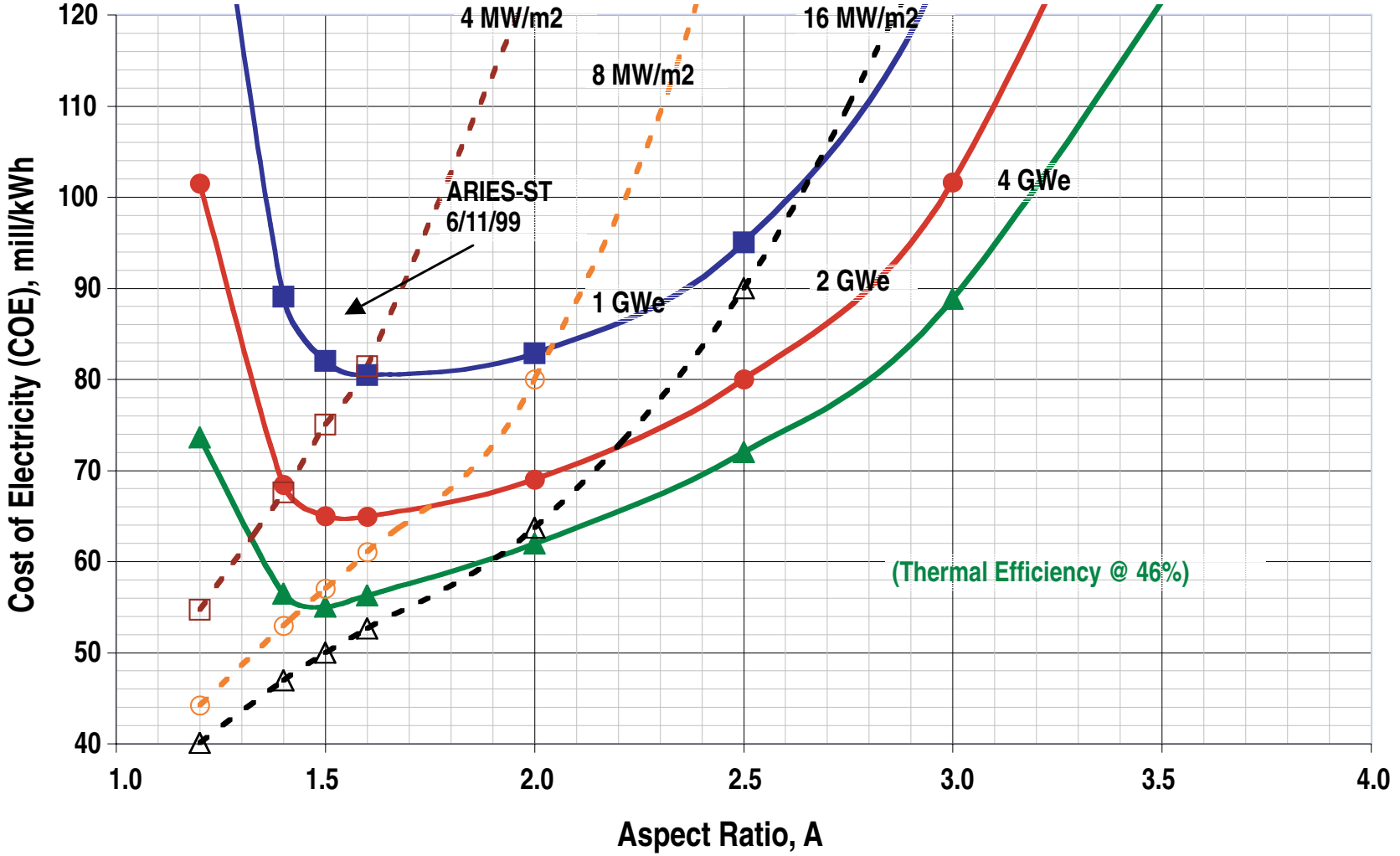
(Central Column Current Density @ 31 MA/m2)



GENERAL ATOMICS

COE OF NORMAL CONDUCTING COIL TOKAMAK REACTORS (1999)

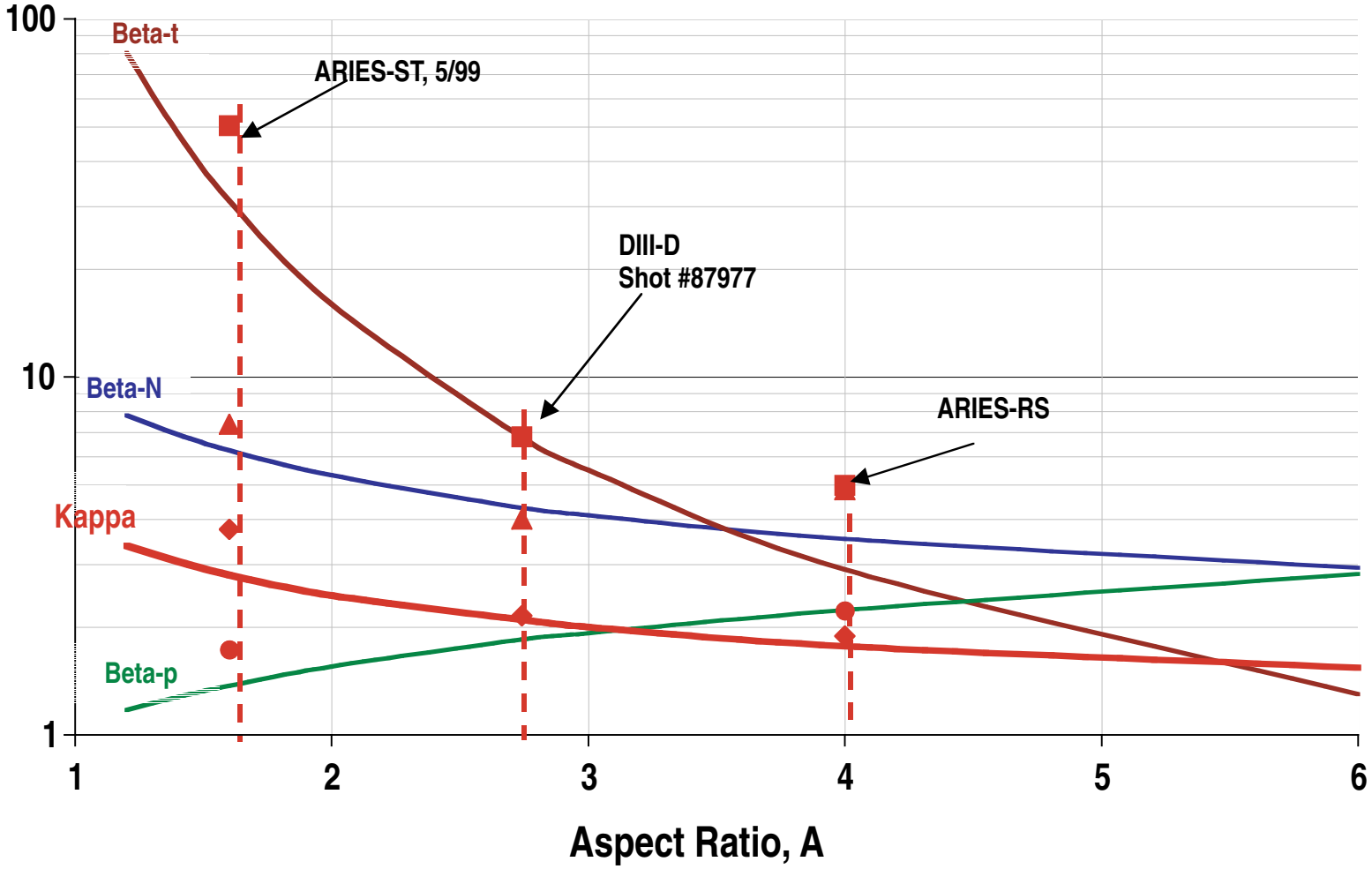
(Central Column Current Density @ 15 MA/m2)



GENERAL ATOMICS

TOKAMAK PHYSICS PARAMETERS (1999)

(Shaping factors: Sn=0.634, St=0.702)



GENERAL ATOMICS

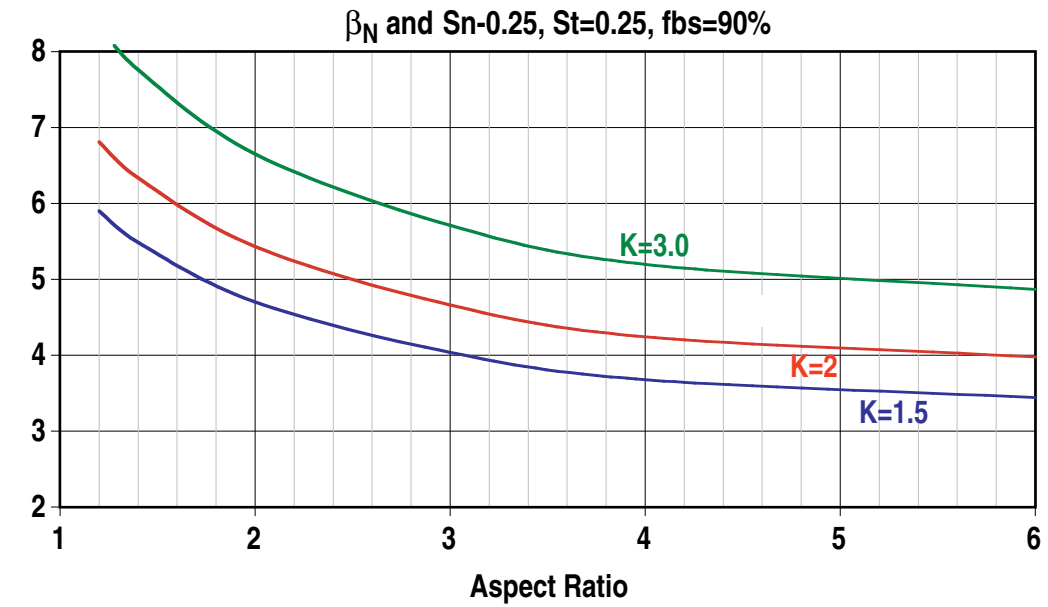
MHD STABILITY BASIS

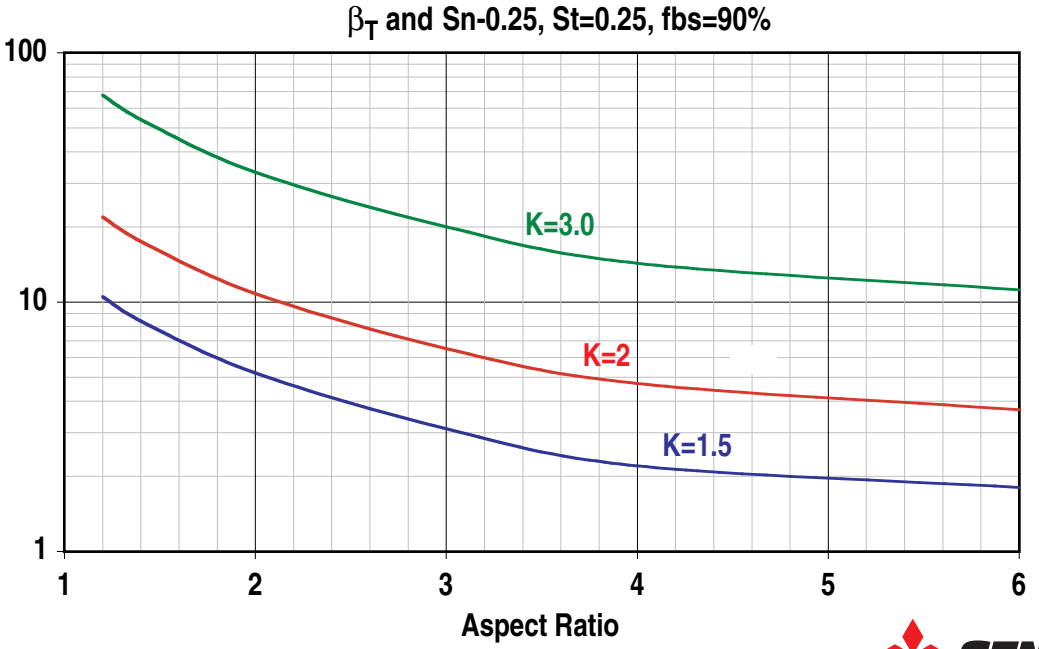
We used the extended equilibra of 1.2<A<6 and κ = 1, 2 and 3.

- For the range of A from 1.2 to 3, Robert Miller* found plasma equilibra that are stable to infinite-n ballooning and with assumed wall stabilization of low-n kink modes at a bootstrap fraction of 99% for κ=1.5, 2 and 3.
- We parametrized these results to perform parametric investigations of A and k variations with our systems modeling.
- For our calculations, we use a bootstrap fraction of 90% to further optimize β_N and β_T, and approximate the power needed for direct (non-bootstrap) current drive and plasma profile control.

* R. Miller et al., "Stable Bootstrap-current Drive Equilibrium for Low Aspect Ratio Tokamaks", ISPP-17 Proceeding, Workshop on Theory of Fusion Plamas, August 26-31, Varenna, 1996.

β_N AND β_T VS ASPECT RATIO





Normalized beta:

$$\beta_N := \frac{\left(3.09 + \frac{3.35}{A} + \frac{3.87}{A^{0.5}}\right) \cdot \left(\frac{\kappa}{3}\right)^{0.5}}{\text{peakfactor}^{0.5}}$$

Toroidal beta:

$$\beta_t := \frac{25}{\beta_p} \cdot \left(\frac{1 + \kappa^2}{2}\right) \cdot \left(\frac{\beta_N}{100}\right)^2$$

Poloidal beta:

$$\beta_t := \text{fbs} \cdot \frac{\sqrt{A}}{\text{Cbs} \cdot \text{peakfactor}^{0.25}}$$

fbs...bootstrap fraction
Cbs...bootstrap coefficient

$$\text{Cbs} := 0.663 + 0.019\kappa$$

Plasma pressure peaking factor:

$$\text{peakfactor} := \left[\int_0^1 \left(1 - x^2\right)^{St} \cdot \left(1 - x^2\right)^{Sn} dx\right]^{-1}$$

METHOD OF CALCULATION (SUMMARY)

A systems study including physics, engineering, costings and with necessary design constraints. (e.g. SC-bore radius, core stresses, Γ_n etc.).

- Starts with the inboard toroidal field (TF) coil radial build, Jc of central column, A, κ, plasma profiles, and δ_x (standoff distance between the coil and the plasma), β_N can be calculated or specified.
- Bo, β_T can be calculated with reactor geometry.
- n_{DT} and fusion power can be calculated.
- Power-electric and neutron wall loading (Γ_n) are determined iteratively.
- COE and direct cost can be estimated.

The power reactor costing:
ARIES systems code, based on 1992$

The test reactor costing:
ITER-FDR design, based on 1999$

INPUT ASSUMPTIONS AND PARAMETERS

Common inputs:

- TF coil resistive power η=90%,
- Blanket energy multiplication, M=1.1,
- Plasma chamber neutron fluence life 15 MW. yr/m^2,
- Plasma triangularity, δ=0.4,
- Density form factor, S_n=0.25,
- Temperature form factor S_T=0.25,
- Mid-plane scrape-off-layer thickness, SOLx=0.05 m,
- Peak plasma temperature, To=20 keV,
- Bootstrap fraction, fbs=90%,
- Additional vertical height for double null divertor chamber 0.5 m each end.

TABLE 1. INPUT PARAMETERS FOR SC AND NC POWER AND TEST REACTORS

Reactor application	Power	Test	Power	Test
TF magnet type	SC	SC	NC	NC
TF central column, Jc, MA/m^2	40	40	15.4	15.4
Number of TF coils	16	16	12	12
Outboard TF coils leg thickness, m	0.2	0.2	0.7	0.7
Inboard coil to FW stand-off, δ_x, m	1.04	1.04	0.25-0.5[1]	0.1
Water coolant volume fraction	NA	NA	0.15	0.15
Water Tin/Tout (°C/°C)	NA	NA	30/50	30/50
Central column taper	1	1	1.5	1.5
Thermal conversion efficiency, %	46	33	46	33

[1]To account for the need for inboard tritium breeding at higher A, the standoff distance δ_x is increased linearly from 0.25 m to 0.5 m for A increasing from 1.2 to 4

Additional constraints:

- Separation SC designs have central bores
  With central column satisfying:
  (Average current, Jc) X (Bave) = constant (ARIES-AT value)

  and

  $R_{bore} \geq 0.5$ m.

- NC designs have no central bore

  Cu-alloy coil Von Mises stress < 138 MPa, water coolant velocity < 10 m/s

- Average neutron wall loading < 8 MW/m^2

Availability = $(294-6*\Gamma_{n,max})/360$

(Basic assumptions:
- Availability would be 75% when the Γ_n is 4 MW/m^2,
- 30 years plant life,
- total FW/blanket change out time: 3 months)

COMPARATIVE RESULTS

Modeled parameters match quite well with the ITER-FEAT design.

- Column 1 ITER-FEAT team parameters.
- Column 2: Code results with input β_N and adjusted fbs.
- Column 3: β-limit model results

	1	2	3
	ITER-FEAT	ITER FEAT	ITER FEAT
Modeling basis	Team	Code	Code, β_{limit}
TF coil type	SC	SC	SC
Total fusion power, MW	500	445	509
Ave. Γ_n, MW/m^2	0.57	0.475	0.543
Ro, m	6.2	6.2	6.2
a, m	2.0	2	2
A	3.1	3.1	3.1
Bootstrap fraction	~0.26	0.26	0.9
n shape factor	no data[1]	0.47	0.25
T shape factor	no data[1]	0.94	0.25
β_N	1.77	1.77	3.74
β_t,%	2.5	2.6	3.2
Ip, MA	15	15.4	8.78
κ	1.7	1.7	1.7
Triangularity	0.33	0.33	0.33
Bo, T	5.3	5.18	5.18
q @ 95% flux surface	3	3.12	5.46
Plasma vol, m^3	837	841	841
Plasma area, m^2	678	726	726
Power Aux., MW	40	96.3[2]	1.5[2]
Power Recir. MW	no data[1]	103.3	8.8
Ave. Ti, keV	8.1	8.1	17.5
n_e/n_{GW}	0.85	1.09	1.
H-factor-89p	no data[1]	2.06	4.2
Zeff	1.65	1.7	1.7
Direct cost[3], $M	3678	4542	4566

[1] Data was not found in published report.
[2] Power approximated by neutral beam current drive at corresponding bootstrap fraction and aux. power.
[3] The direct cost includes the tokamak, ancillary, power and facility costs.

GENERAL ATOMICS

1 GWe SC AND NC REACTOR DESIGNS

Showing the design trade offs between physics and toroidal chamber geometry

- To maintain output power, decreased physics performance due to higher A and/or lower κ, the reactor size needs to be increased leading to a lower wall loading and higher COE.

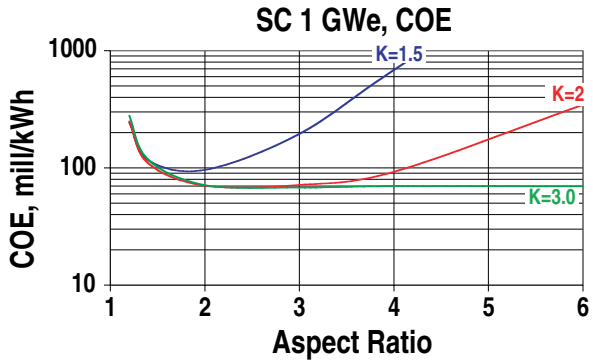
- On the other hand, as A falls below 2, due to geometry the first wall area increases.

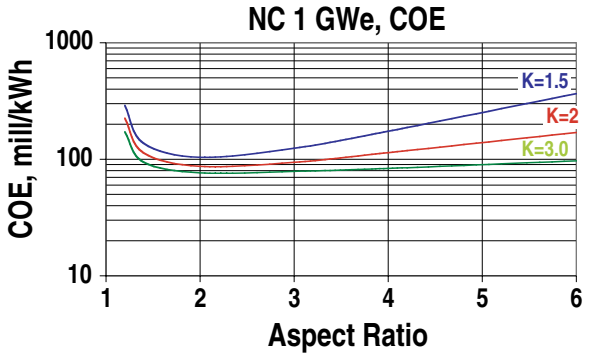
These effects (adding to design constraints) lead to a maximum in Γ_n and a minimum in COE as a function of A.

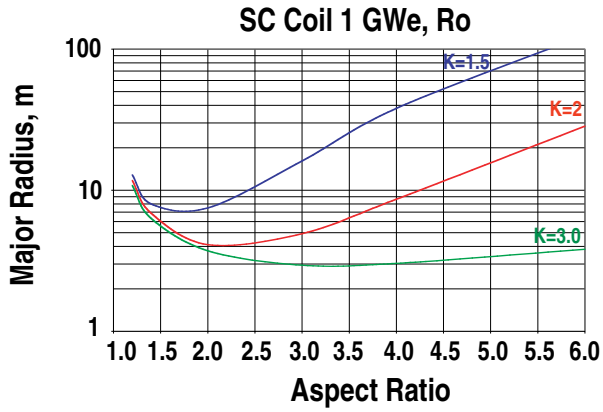
- COE is near-minimum for A ~ 2 and the minimum becomes broader for higher κ

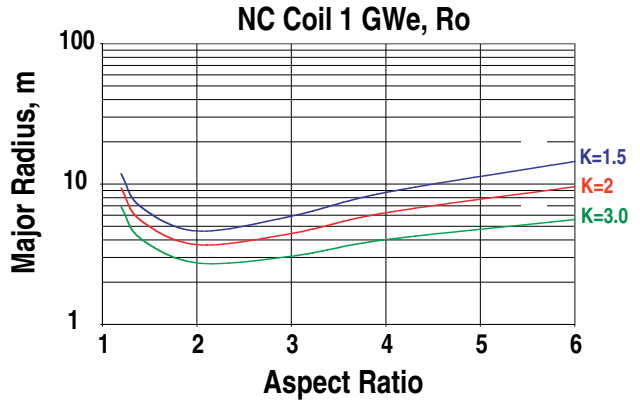
- Plasma densities required normalized to the Greenwald $n_{GW}(10^{20}\ m^{-3}) = I(MA)/a^2(m)$ decrease for higher κ. (Experiments will be needed to show the possibility of the possibility of the design cases with $n_e \geq n_{GW}$.)

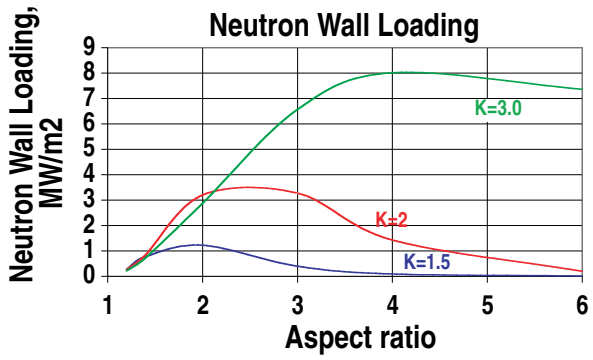
1 GWe SC AND NC REACTOR DESIGNS PARAMETERS (1)

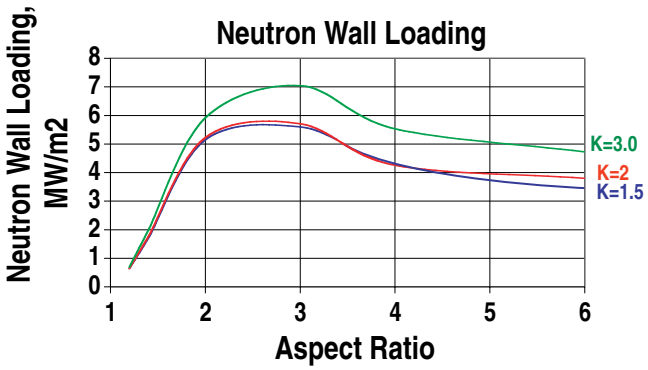












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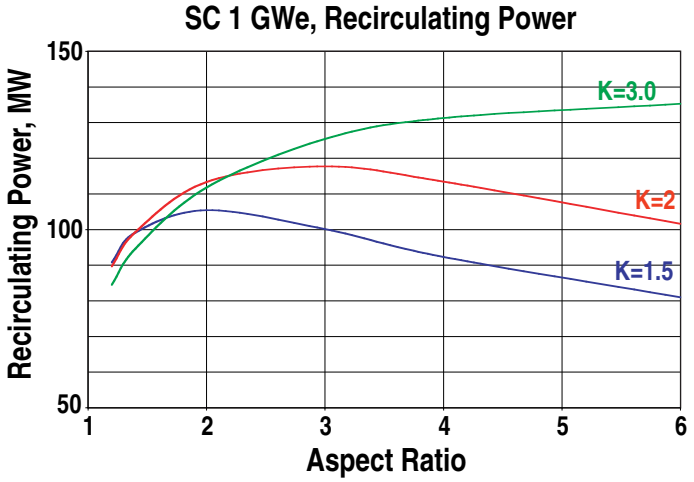
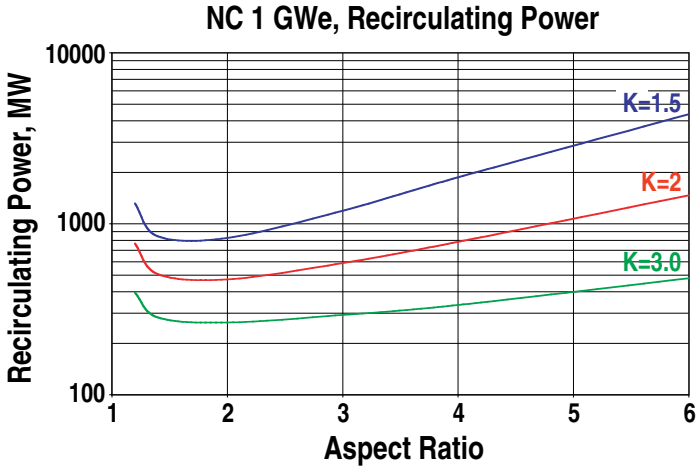
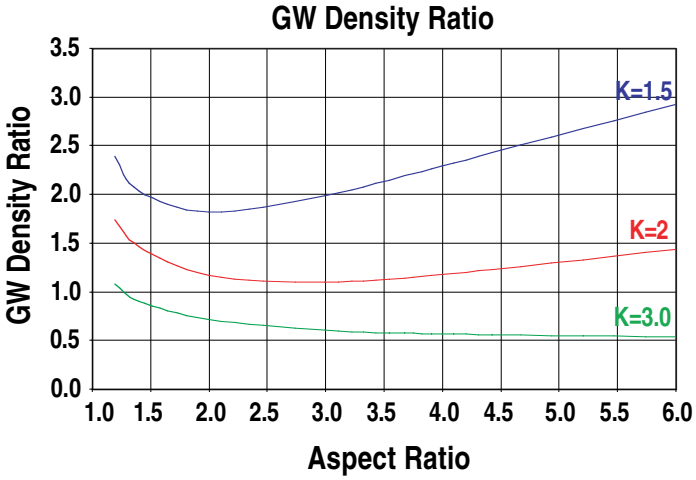
GENERAL ATOMICS

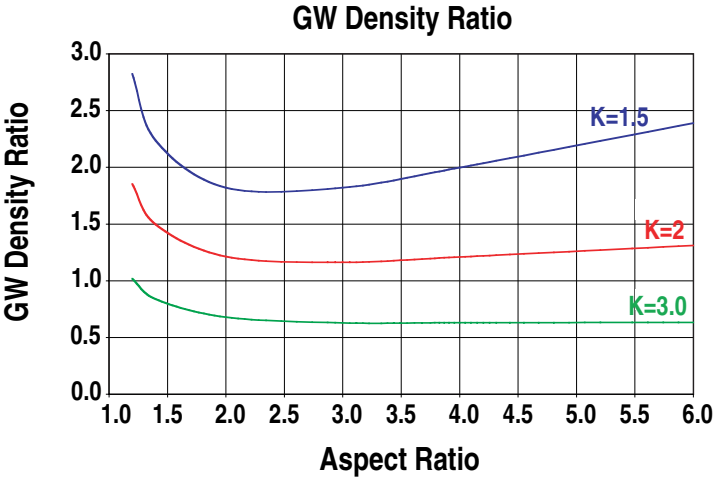
233-00 jy

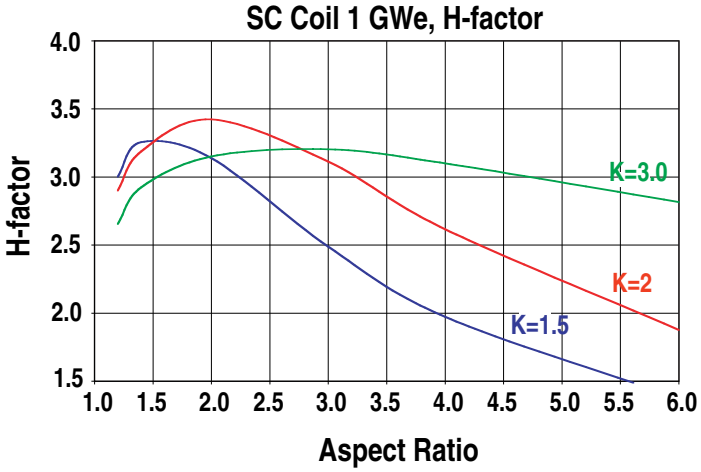
1 GWe SC AND NC REACTOR DESIGNS PARAMETERS (2)

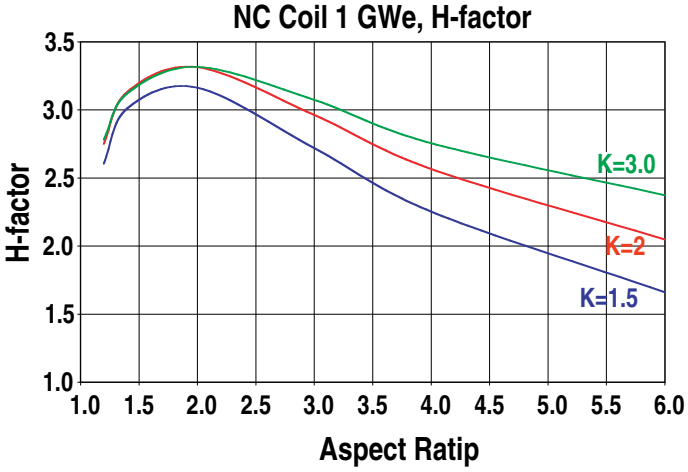












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DETAIL COMPARISON OF SC AND NC DESIGNS

An A=2 and κ=3 testing reactor may be a suitable device to prepare the development for SC and NC power reactors.

Power Reactors:

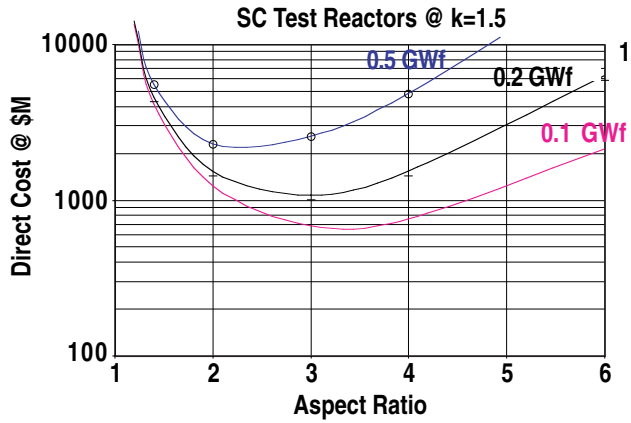
- Reactor designs have minimum COE towards lower A~2. Higher k allows broader minimum.
- SC and NC COEs are similar.
- Reduction in COE due to higher power output is more distinct for NC designs.

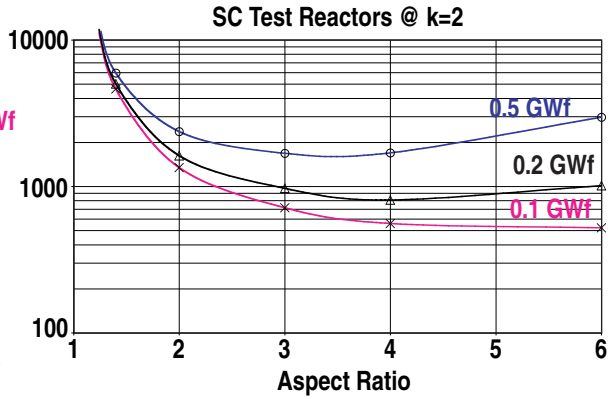
Testing Reactors:

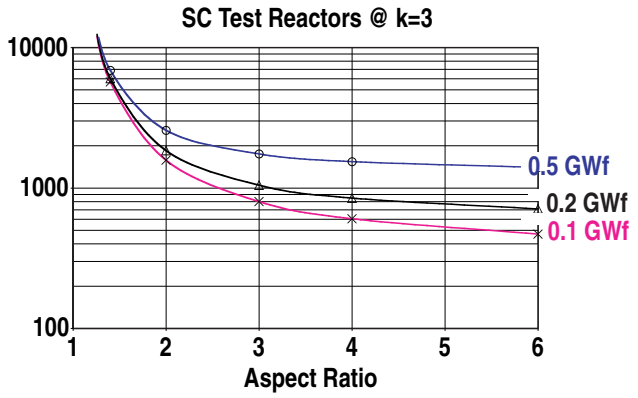
- For the same power output NC design direct cost is much lower than SC design direct cost.
- A=2 designs have ~ 15% high direct cost than A=3 designs.
- Higher κ allows lower direct cost.

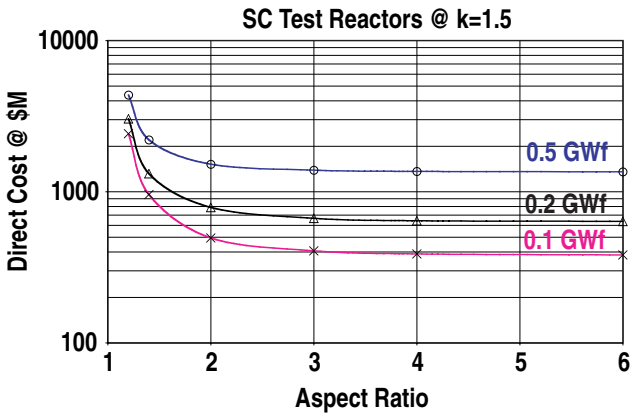
SC AND NC TEST REACTORS

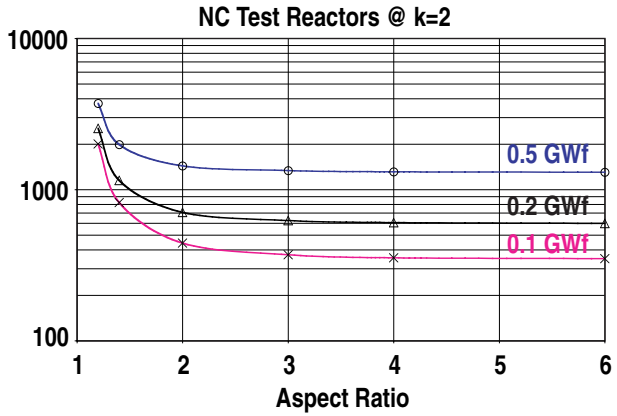
(T-peak at 20 keV, f_{bs} = 90%, and S_n=0.25, S_t = 0.25)

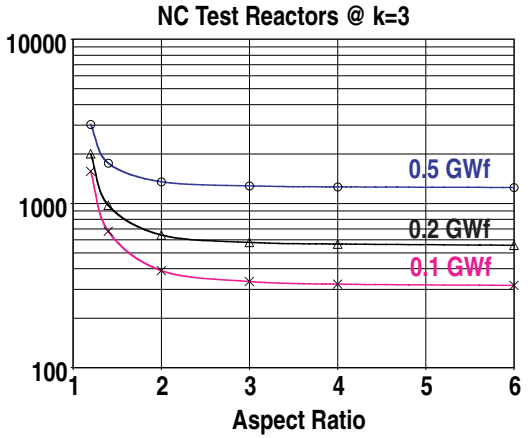












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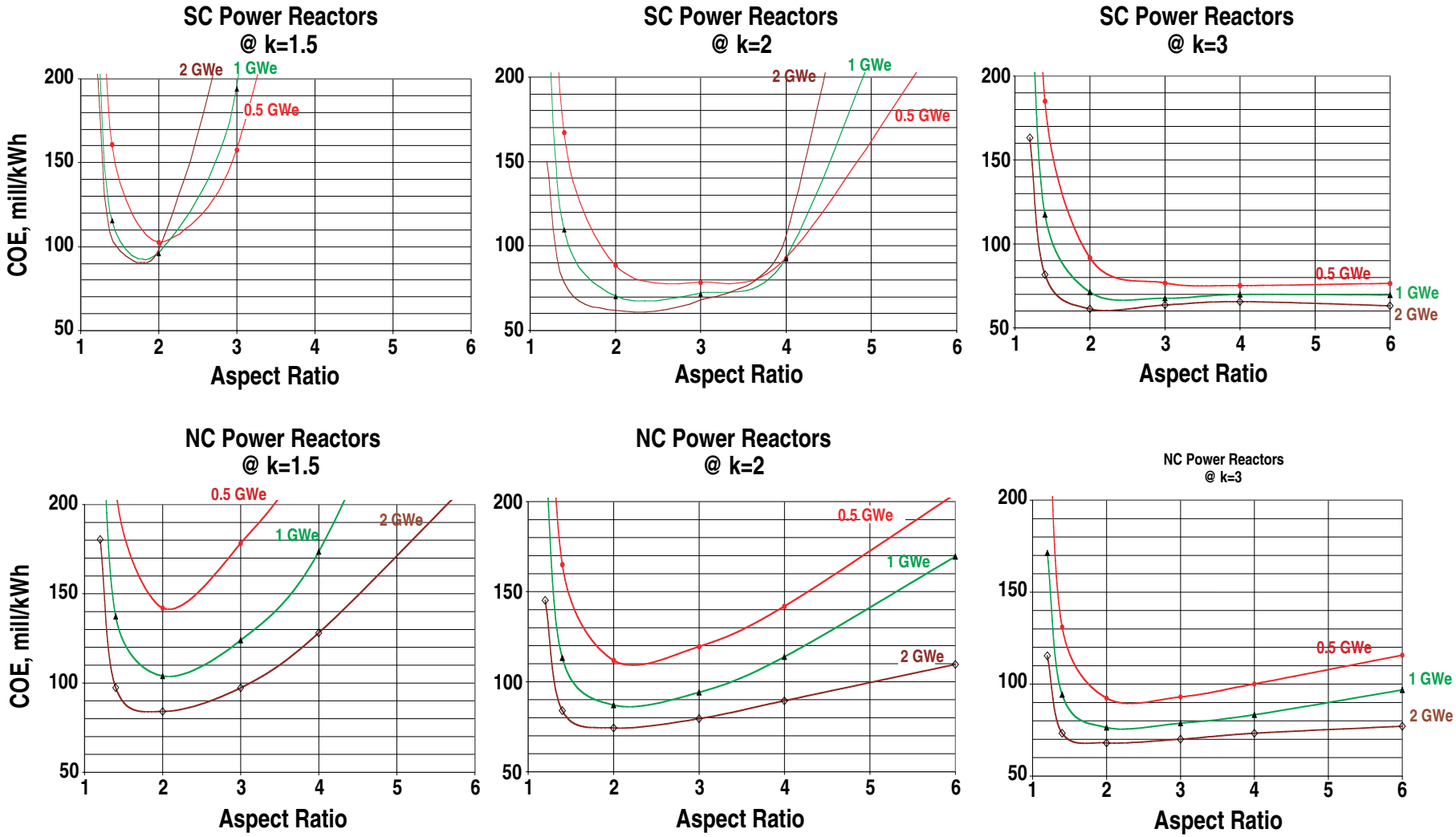
SC AND NC POWER REACTORS

(T-peak at 20keV, fbs=90%, and Sn=0.25, St=0.25)



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GENERAL ATOMICS

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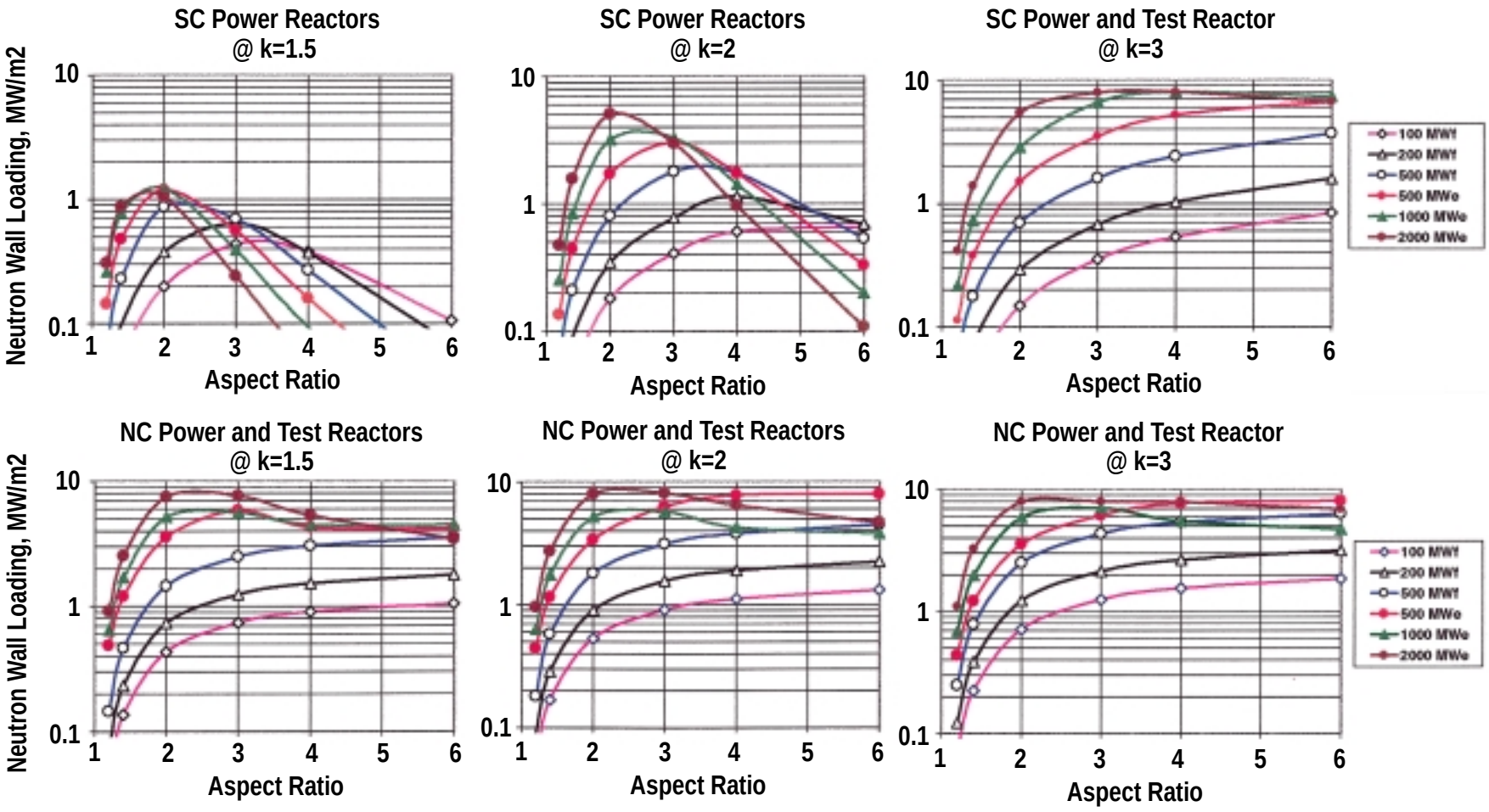
NEUTRON WALL LOADING FOR SC AND NC POWER AND TEST REACTORS

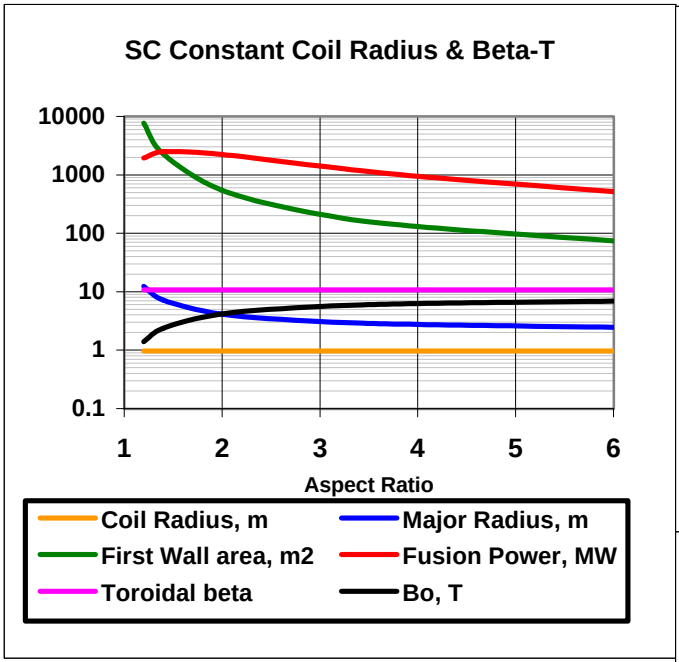
(T-peak at 20keV, fbs=90%, and Sn=0.25, St=0.25)

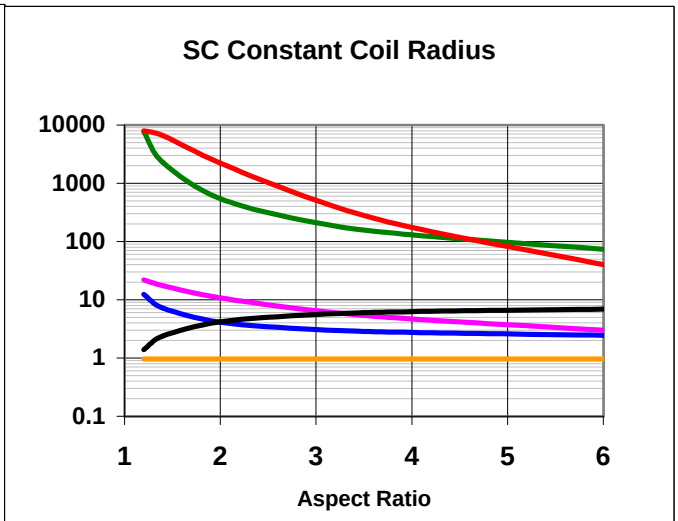


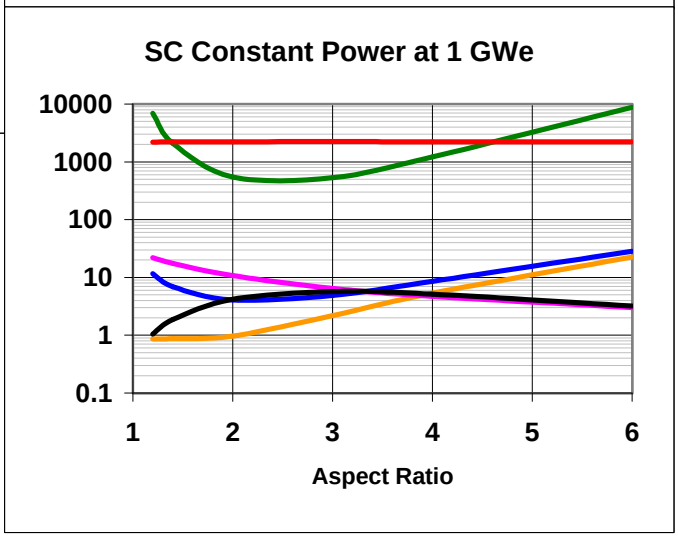
GENERAL ATOMICS

EVOLUTION OF DESIGN PARAMETERS AT ELONGATION

Cases for superconducing coil designs







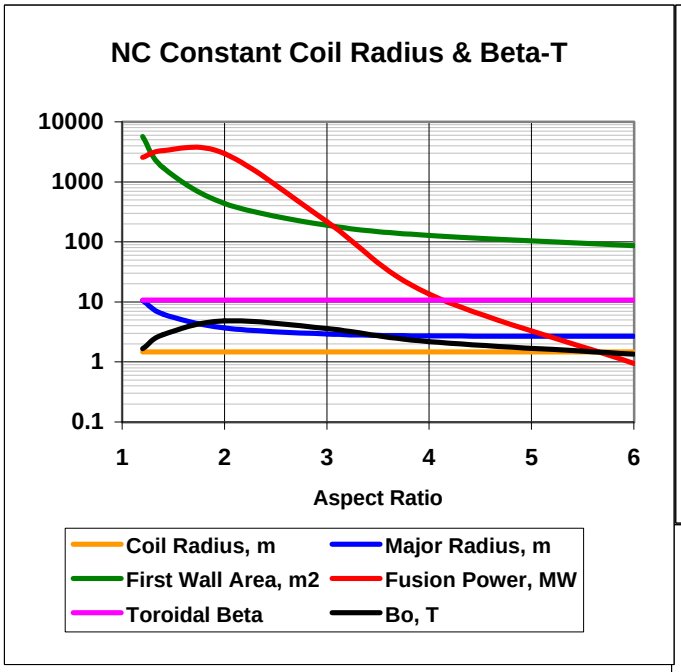
Steady state Tokamaks performance depends on:

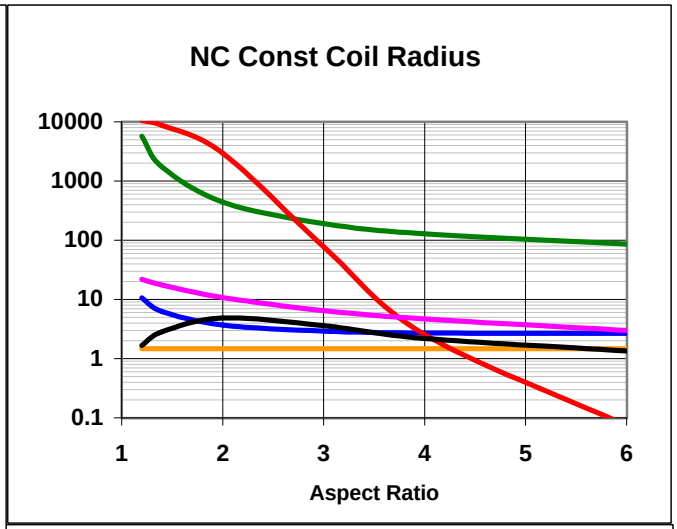
Geometry
Equilibrium physics
Desired power output
yet confinement & plasma stability requirements are not included here*

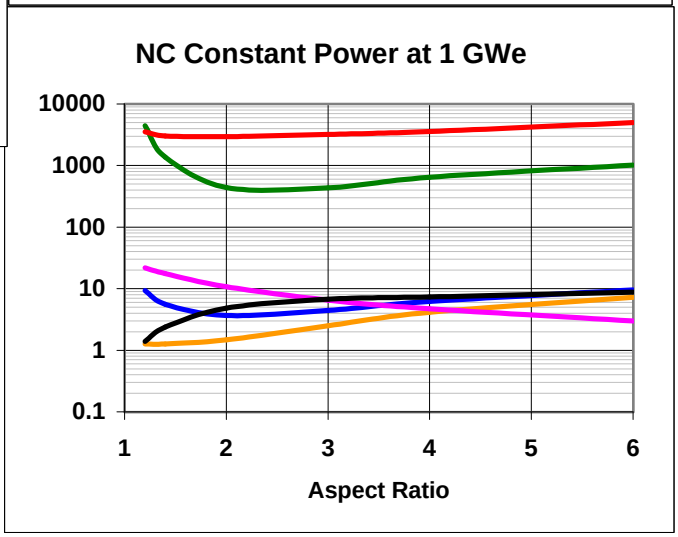
*** Parameters like H-factor and density limit are calculated but not designed to.**

EVOLUTION OF DESIGN PARAMETERS AT ELONGATION

Cases for normal conducting coil designs







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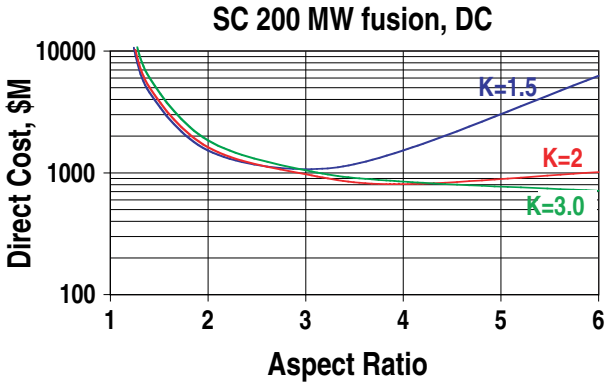
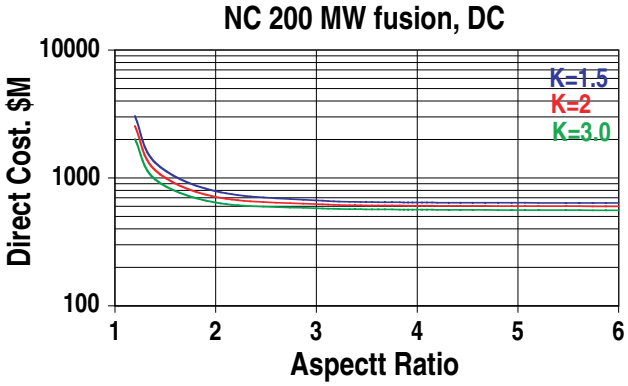
200 GW FUSION SC AND NC TEST REACTOR DESIGNS

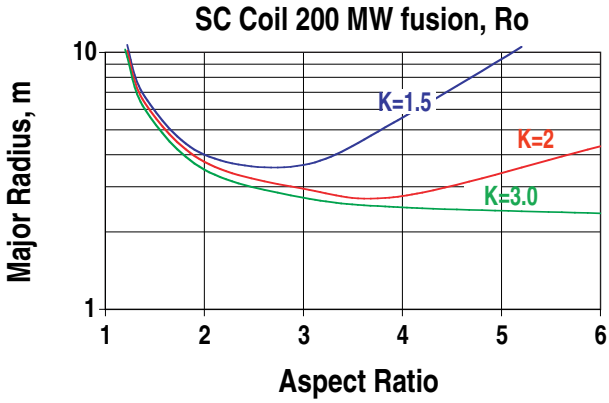
NC designs have much lower direct cost than SC designs.
For the same power output, NC allows higher neutron wall loading.

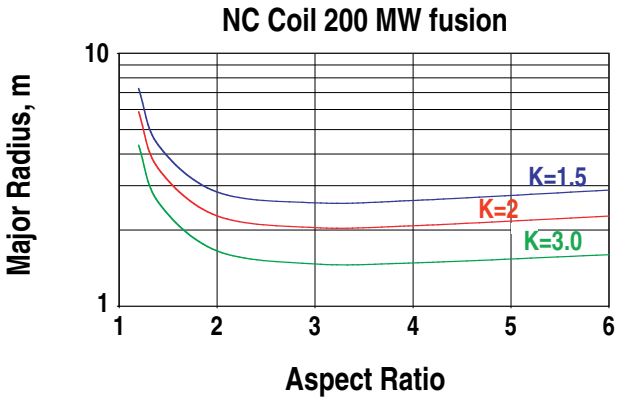
- **NC designs have higher re-circulating power.**
- **Testing devices require higher H-factor.**

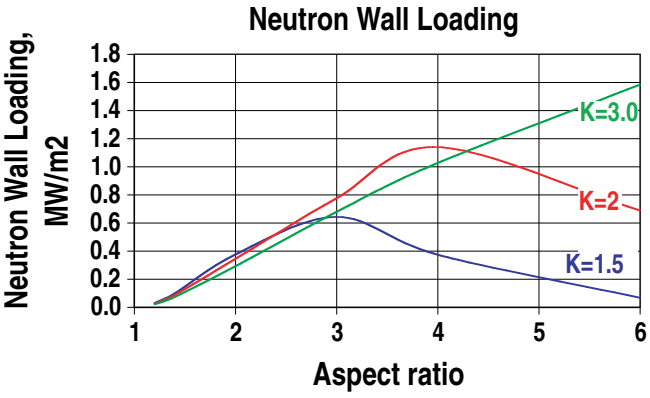
200 MW fusion SC and NC Coil Testing Reactors (1)

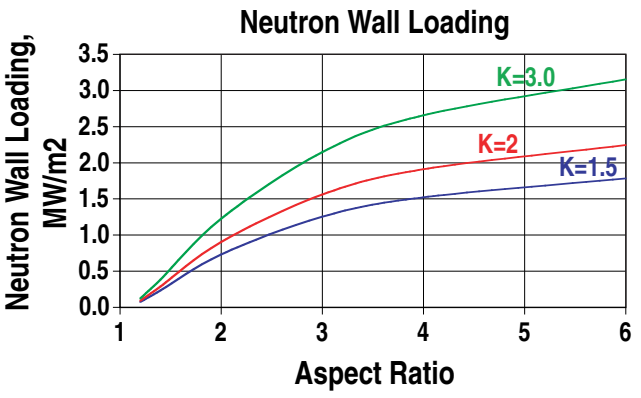




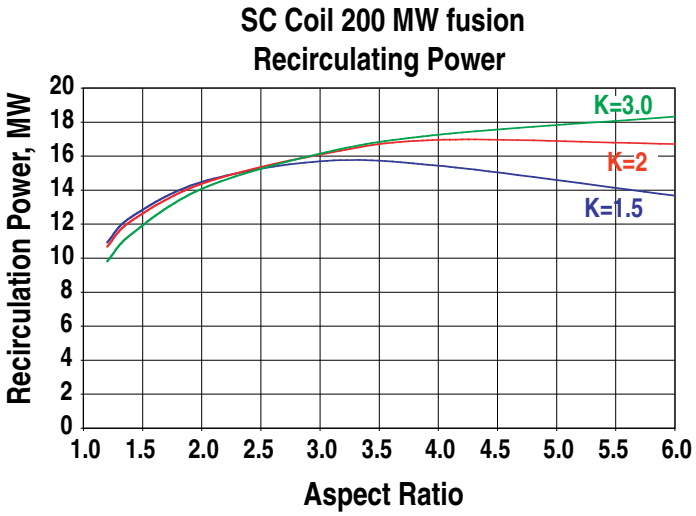


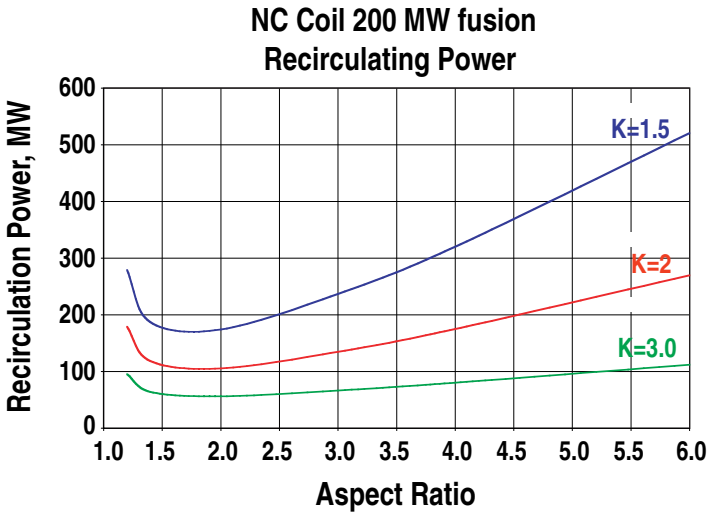


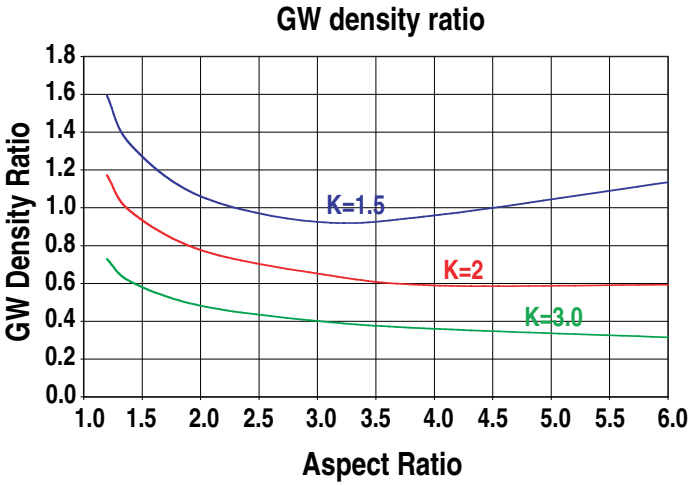


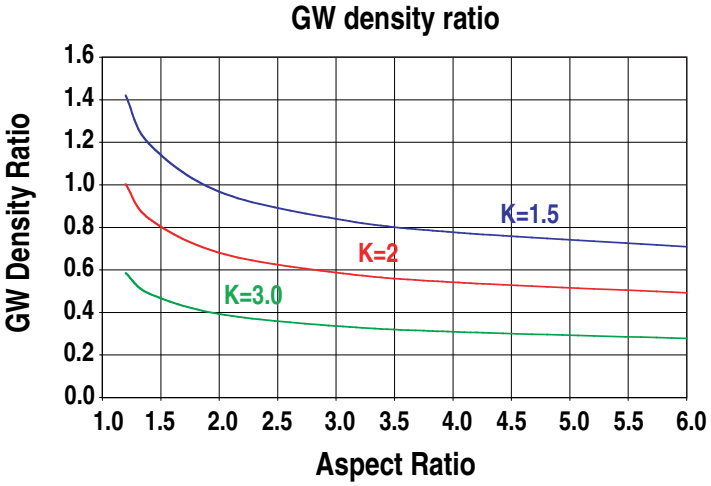


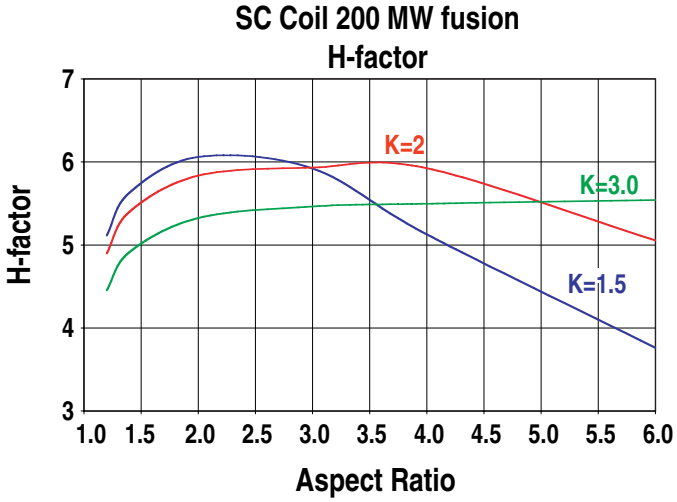
200 MW fusion SC and NC Coil Testing Reactors (2)

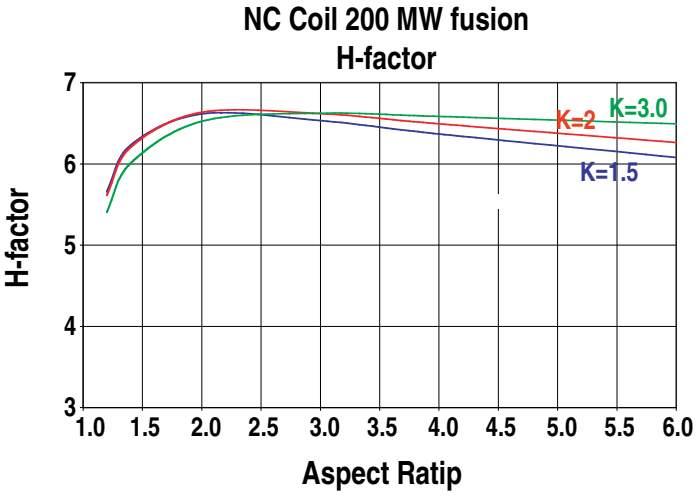












GA Wong 2000

GENERAL ATOMICS

233-00 jy

EXAMPLE OF AN A=2, κ=3, 200 MW FUSION TEST REACTOR

(An interesting next-step D-T burn device)

Modeling basis	Code, $\beta_{limited}$	Ip, MA	9.44
TF coil type	NC	q @ 95% flux surface	5
Ro, m	1.656	n_e/n_{GW}	0.31
a, m	0.828	H-factor-89p	6.5
Bootstrap fraction	0.9	Zeff	2.08
n shape factor	0.25	Plasma vol, m^3	70.6
T shape factor	0.25	Plasma area, m^2	124.8
β_N	6.65	Power Aux., MW	0.93[1]
β_t,%	33.2	Power Recir. MW	56[2]
Triangularity	0.4	Ave. Γ_n, MW/m^2	1.23
Bo, T	2.28	Fusion power, MW	200
Ave. Ti, keV	17.5	Direct cost, $M	643

[1] Power approximated by neutral beam current drive at corresponding bootstrap fraction.
[2] Current drive power and auxiliary power.

Summary:

- 200 MW fusion testing reactor
- Direct cost of <$650 M
- Average Γ_n of 1.23 MW/m^2, adequate for fusion components nuclear testing
- The scientific knowledge from this design could be applicable for SC and NC power reactor development

Neutron Applications:

e.g. Burning of fission reactor waste materials. With a fissile blanket energy multiplication of 20, η_{th}=33%, net power=977 NWe, with COE at 62 mill/kWh and could convert about ~1270 kg of fission reactor waste per full power year. (The COE estimated here does not include costs for the handling of fissile materials. However, the revenue generated from the disposal of fission reactor wastes may compensate for the extra costs incurred.)

CONCLUSIONS

With the scan of A and κ impacts to power reactor and testing reactor designs indicate an intermediate-A NC design with high elongation could provide scientific and testing data to support future SC or NC reactors. This may be a device that could reduce the development cost of fusion.

- Designs of steady state SC and NC power and test reactors have been studied as a function of A and for κ=1.5, 2 and 3.
- The effect of MHD stability as a function of A and κ is included.
- Considering the design uncertainties inimum COEs of SC and NC power reactors are similar.
- Reactor designs have minimum COEs moving towards A~2. Higher κ allows broader minimum.
- Direct cost of NC test reactors, for similar fusion power, is significantly lower than equivalent SC designs.
- A NC test reactor at A~2 and κ~ 3 could produce 200 MW fusion power at 1.23 MW/m^2 average Γ_n at a total direct cost of ~$643 M.
- This device could also be a reactor for early application of fusion neutrons and convert ~1270 kg of fission reactor waste per full power year.