Analysis of Systems Code Results

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Motivation for This Talk

- **Questions regarding costing in code**
  - **Farrokh: "in ISW paper, CS device has 60% more weight than ARIES-AT and a lower COE"**
  - **NCSX CS: mass = 12,102 tonnes (15% more)**
    COE = 55.7 mills/kW-hr (1992)
  - **ARIES-AT: mass = 10,495 tonnes**
    COE = 56.6 mills/kW-hr (1992)
- **Would like to compare the ARIES-CS cost machine parameters and cost numbers with our older designs**
  - **i.e., ARIES-AT and ARIES-RS**

Topics

- NCSX-ARE reference case parameters
- Component volume formulas and values
  - blanket/shield/manifold/vacuum vessel
  - coils and associated structure
- Cost and density database used
- Detailed component masses and costs
  - blanket/shield/manifold/vacuum vessel
  - coils and associated structure
- Costing for each subaccount and comparison with earlier ARIES reactor cases

Plasma and Coil Parameters

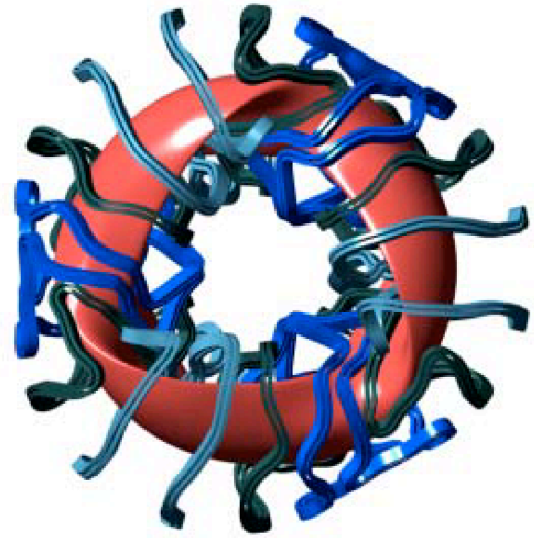
Configuration	MHH2 K14LA	NCSX ARE
# of Period	2	3
Plasma Aspect Ratio	2.66	4.55
Plasma β @ optimization (%)	5.00	4.06
Plasma Current, I/R-B (MA/m-T)	0.201	0.072
Normalized Plasma Volume, Vol/R^3	2.793	0.950
Normalized Plasma Surface Area/R^2	18.547	11.780
$\iota(s = 0)$	0.33	0.42
$\iota(s = 0.67)$	0.48	0.64
$\iota(s = 1.0)$	0.58	0.66
Epsilon effective (%), max	~0.8	~0.6
Alpha energy loss (%), model calc.	~5	~10
# of Coil Type	4	3
# Coils/Period	8	6
Total # of Coils	16	18
Coil Aspect Ratio: R/Δ_{min}(coil-plasma)	5.55	5.89
Coil Separation Ratio: R/Δ_{min}(coil-coil)	10.33	10.03

Plasma and Coil Parameters

Configuration	MHH2 K14LA	NCSX ARE
Normalized Max. Coil Current: I/R-B (MA/m-T)	0.316	0.306
Normalized Coil Lengths: L/R; Coil 1	6.14	4.77
Coil 2	5.83	5.08
Coil 3	5.52	5.14
Coil 4	5.25	-----
Normalized Winding Surface Area: Area/R^2	40.1	27.0
Normalized Max Field in Coils: $B_{max}/B(0)$ 0.20 m x 0.20 m	4.27	4.02
0.30 m x 0.30 m	2.69	2.63
0.40 m x 0.40 m	1.94	2.10
0.50 m x 0.50 m	1.72	1.85
0.60 m x 0.60 m	1.60	1.70
0.80 m x 0.80 m	1.46	1.59

Reference Plasma and Coil Configurations

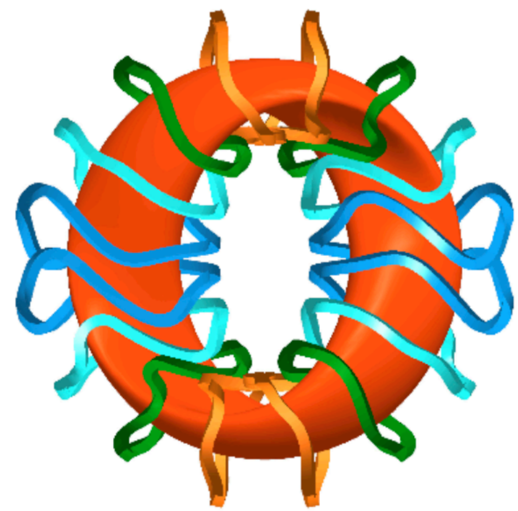
Key Configuration Properties	ARE	LA14
Plasma aspect ratio $A_p = \langle R \rangle / \langle a \rangle$	4.55	2.66
Plasma surface area/$\langle R \rangle^2$	11.78	18.55
Minimum pl-coil dist. ratio $A_\Delta = \langle R \rangle / \Delta_{min}$	5.89	5.55
Minimum coil-coil dist. ratio $\langle R \rangle$/(c-c)	10.03	10.33
Total coil length/$\langle R \rangle$	89.3	91.0
Coil winding surface/$\langle R \rangle^2$	40.1	27.0
$B_{max}/\langle B_{axis} \rangle$, 0.3 m x 0.3 m coil pack	2.63	2.69



NCSX-ARE

NCSX-ARE example

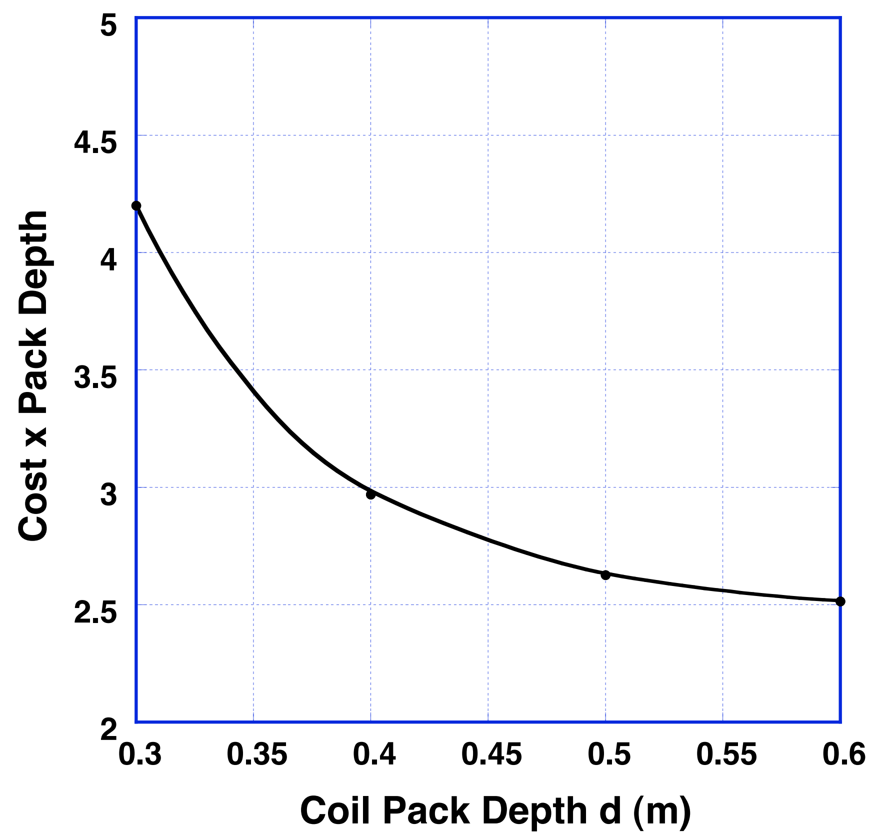
- For 5 MW/m² max. on wall, $\langle R \rangle_{min}$ = 6.85 m
  - (11.78 R^2)(1+0.05/1.522)(5/1.52) = 18.78.6 MW
- For coil depth = 0.184 m, $\langle R \rangle_{min}$ = 6.61 m
  - R = 5.89 x (0.05 +0.038 +0.17 +0.05 +0.38 +0.02 +0.28 +0.02 +0.022 +0.184/2)
- Code gives $\langle R \rangle$ = 6.93 m for $\langle \beta \rangle$ = 5%



MHH2-LA14

Code Minimizes COE

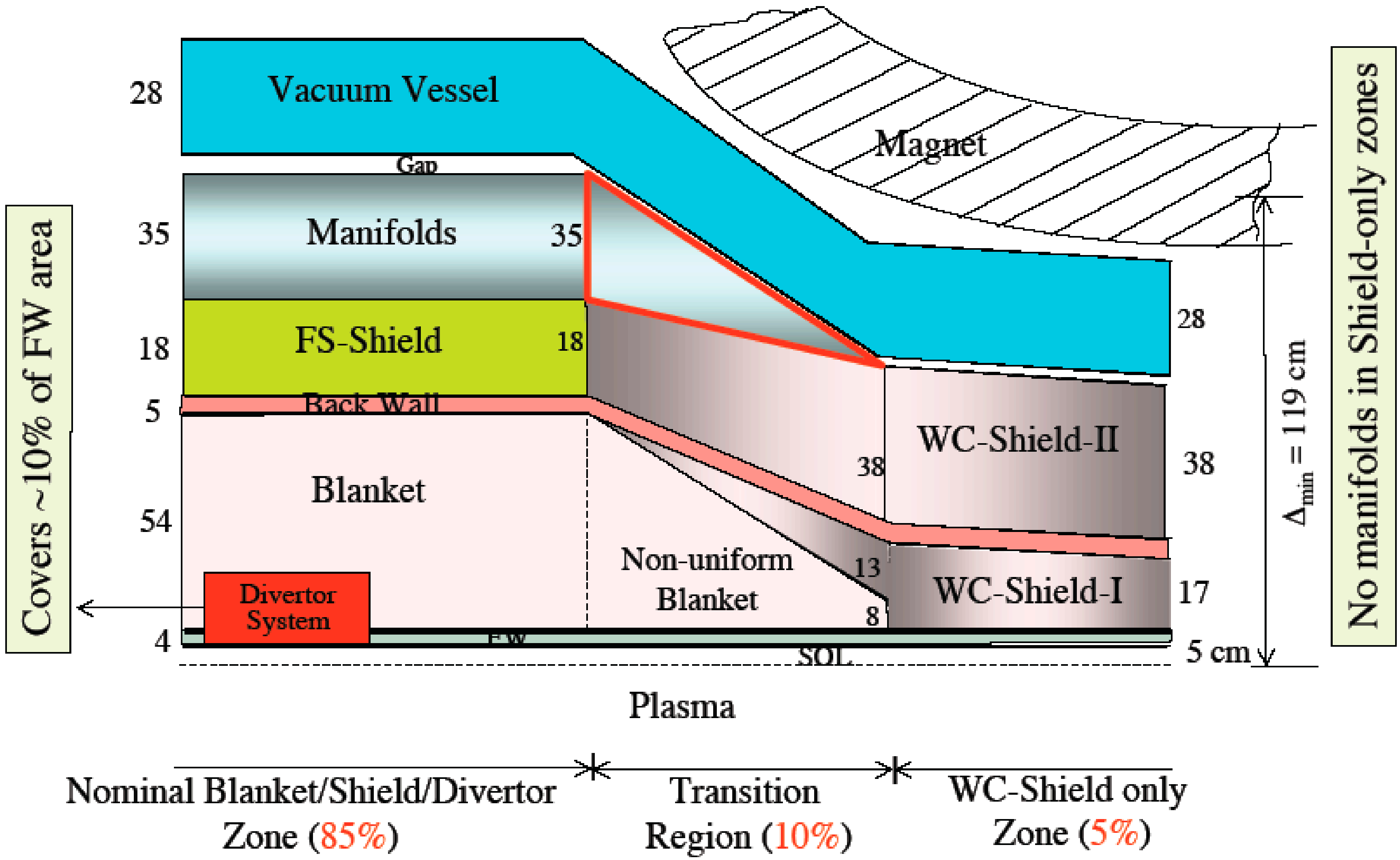
- Since radial thicknesses of most components are approx. fixed, volumes (and costs) ~ areas ~R^2, so code minimizes $\langle R_{axis} \rangle$
- $\langle R_{axis} \rangle$ set by *larger* of $(5/p_{wall,max})^{1/2}$ or $A_{\Delta}D$
  - fixes I_{coil}, L_{coil}, coil-coil spacing and hence coil elongation
- Maximum half-coil-radial-depth set by space between vacuum vessel and coil winding surface
  - ⇒ minimize cost by using maximum coil thickness
  - j_{coil} and B_{max} decrease, cost decreases faster than coil volume (thickness) increases



NCSX-ARE Reference Parameters

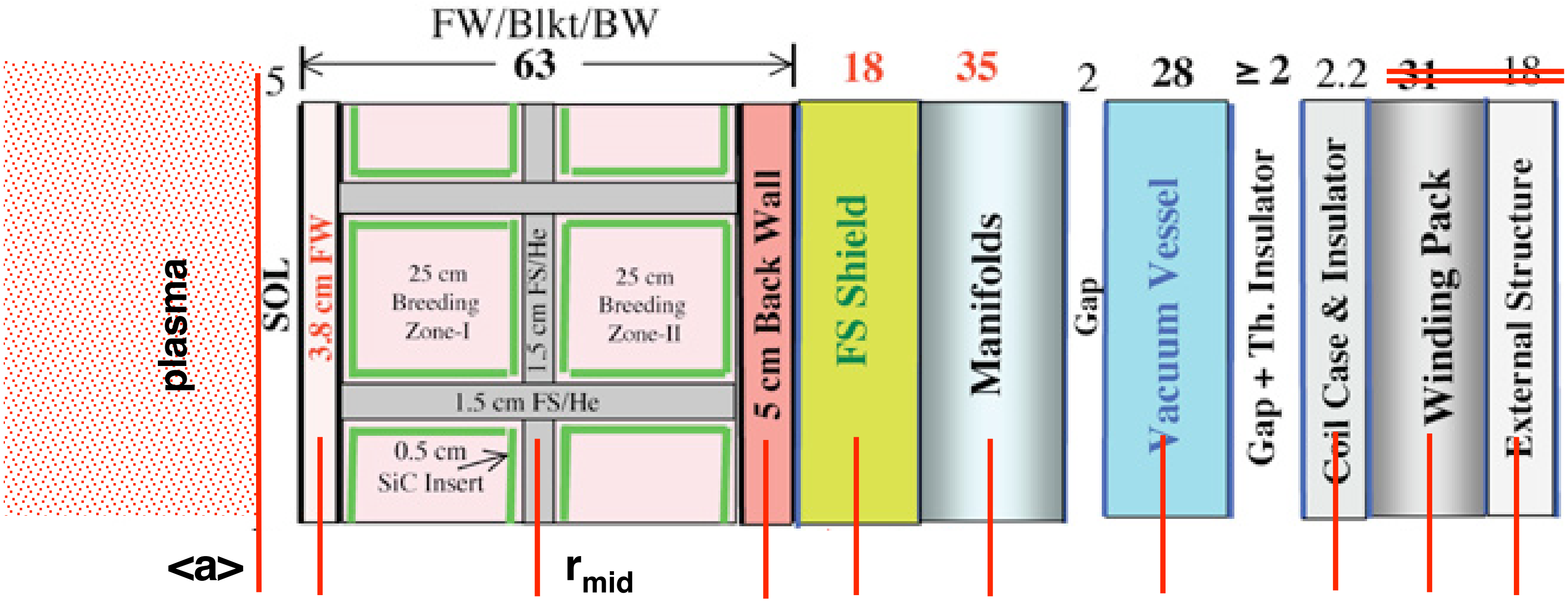
- **Reactor Parameters**
  - Electric Power = 1 GW
  - $\langle R \rangle / \langle R \rangle_{min}$ = 1.000
  - max. neutron wall load 4.89 MW/m^2 (<5 MW/m^2)
    - $\langle R \rangle$ only 1% larger than $p_{n,wall}$ limit
  - max. magnetic field at coil B_{max} = 14.03 T (<16 T)
  - current density 107.6 MA/m^2, j_{coil}/j_{max} = 1.00
  - port width 3.64 m & 2.36 m (>2 m)
  - average plasma density 4.59 x 10^{20}/m^2,
    $\langle n \rangle / 2n_{Sudo}$ = 1.00
  - ave. major radius $\langle R_{axis} \rangle$ = 6.93 m
  - ave. field on axis $\langle B_{axis} \rangle$ = 6.28 T
  - coil pack dimensions 0.184 m x 0.671 m
  - Cost of Electricity 55.7 mills/kW-hr (1992 $)

Radial/Toroidal Cross Section



- **Shield thickness is corrected for ln($p_{n,wall}$) term in code**

Calculation of Volumes

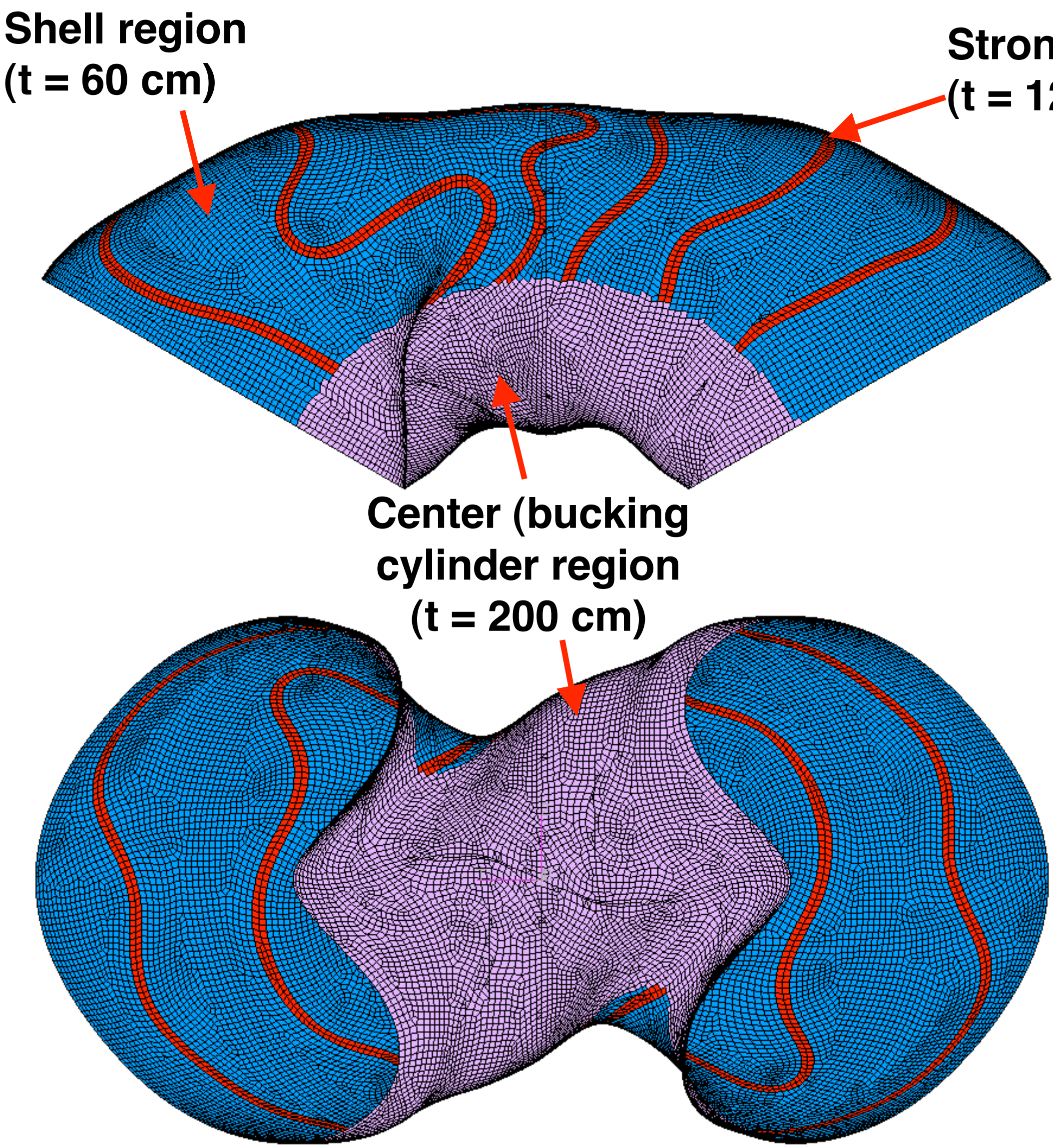


- volume = mid-radius surface area (scaled radially from plasma surface area) x thickness
  - can shift to mid-radius normalized from CAD calculation when redone for $\langle R\rangle$ ~ 7 m and can interpolate from $\langle R\rangle$ = 8.25 value
- e.g., for FS shield, volume = [plasma surface area] x (<a> + 5 + 63 + 18/2)/<a> x 18 = [11.78 x $\langle R\rangle^2$] x (<a> + 77)/<a> x 18 = 153.2 m^3
- mass = 153.2 x 7.02 = 1075 t; cost = 153.2 x 222.69 = 34.11 M$
- code: vol = 160.9 m^3, mass = 1129 t, cost = 35.7 M$ with $\ln(p_{wall})$ term

Calculation of Coil-Associated Volumes

- **Coil winding pack (NCSX-ARE example)**
  - volume = length x cross section = 35.11 m^3
  - length = 6(4.77 + 5.08 + 5.15)R = 90R = 622.96 m
  - cross section = (R/10.03 – 0.02)$depth_{coil}$ or I_{coil}/j_{coil} = (0.306RB)/j_{coil}
  - coil winding surface = 27.0R^2 = $R\langle a_{coil}\rangle$[plasma surface]/($R\langle a\rangle$), so $\langle a_{coil}\rangle$ = (27/11.78)$\langle a\rangle$ = 2.29R/4.55 = 0.504R
- **Need to correct for thickness (~B^2R^2) & area of mid surface ($\langle R_{axis}\rangle$, r_{mid}, cumulative thickness corrections)**
  - Wang and Williamson used $\langle R\rangle$ = 8.25 m, $\langle B\rangle$ = 5.3 T
  - Bromberg used $\langle R\rangle$ = 6.73 m, $\langle B\rangle$ = 6.2 T
  - code has $\langle R\rangle$ = 6.93 m, $\langle B\rangle$ = 6.28 T
  - B^2R^2 correction = 0.99 (Wang, Williamson), 1.09 (Bromberg)
- **Used NCSX-ARE and corrected Bromberg values so far; need to decide on best approach**

D. Williamson’s 3-D Model (*before* corrections)



Coil Structure Surface Area (Field Period)

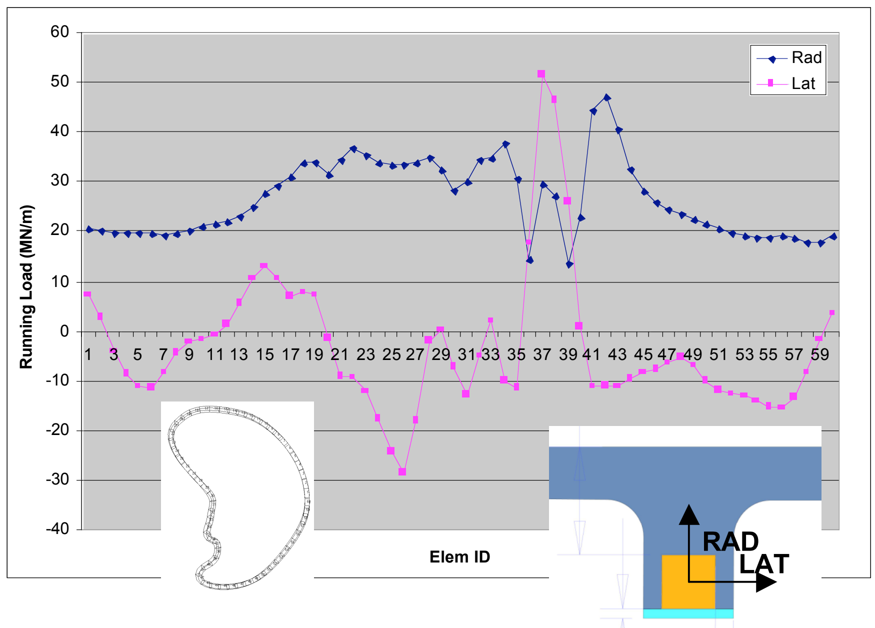
Inboard Region (Bucking Cylinder)	**198.4**
Strongback	**33.1**
Shell	**165.3**
Outboard Region	**410.4**
Strongback	**45.0**
Shell	**365.4**
Openings	
~1/3 of outboard shell area	**- 120.6**
Total	**488.2**

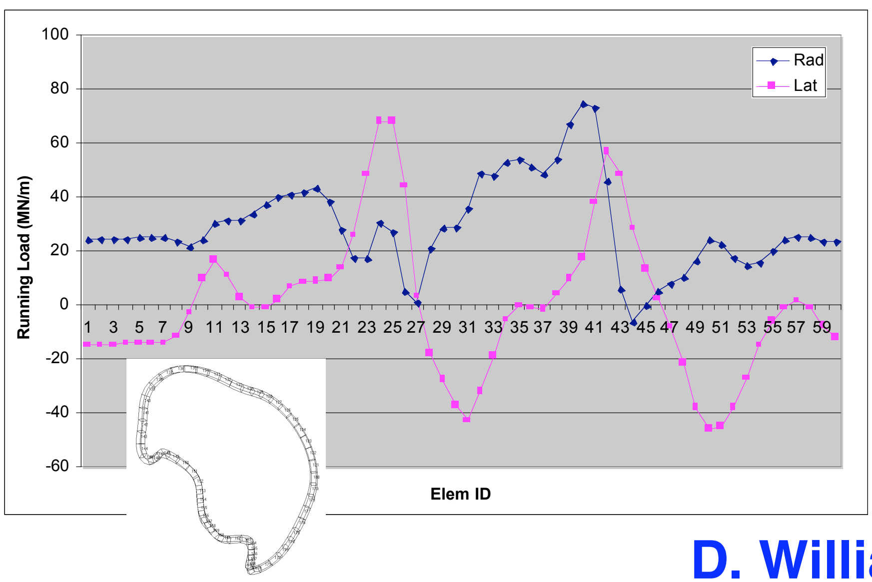
Coil-Associated Thicknesses

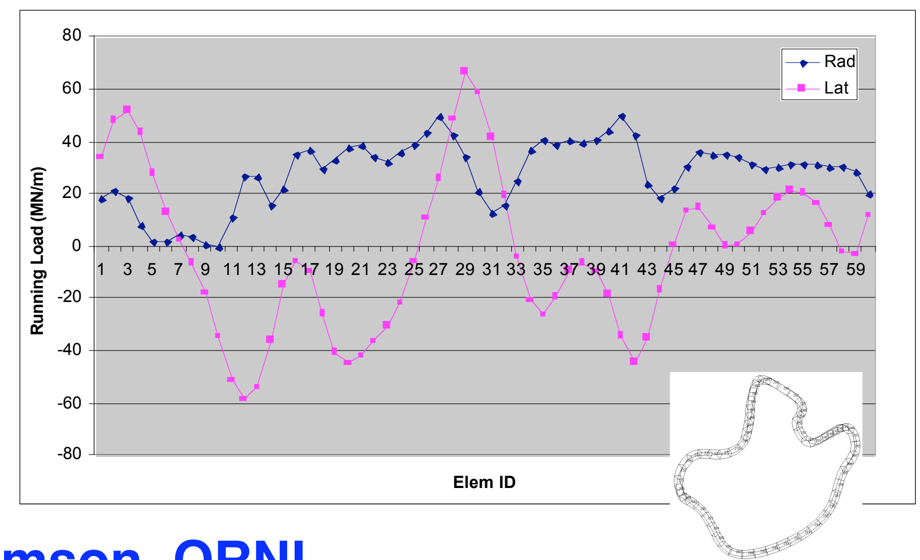
- Strongback behind coils:
  - Bromberg: thickness = 49-61 cm (average = 58.8 cm) ==> 64.0 cm
  - Wang: thickness ~ 65 cm ==> 64.4 cm
  - Williamson: thickness = 120 cm x 3/8 = 45 cm ==> 44.6 cm
- Shell between coils:
  - Bromberg: thickness = 10 cm ==> 10.9 cm
  - Wang: thickness ~ 35 cm ==> 34.7 cm
  - Williamson: thickness = 60 cm x 3/8 = 22.5 cm ==> 22.3 cm
- Bucking cylinder behind strongback on small-R side:
  - Bromberg: thickness = 27.5 cm ==> 29.9 cm
  - Wang: thickness ~ 85 cm ==> 84.2 cm
  - Williamson: thickness = 200 cm x 3/8 = 75 ==> 74.3 cm
- Used Bromberg's values scaled by B^2R^2

Need to Revise Coil-Associated Thicknesses

- **Sides need to be as thick or thicker than strongback *at some points* along the coil circumference!**
- **Radial forces only outward**







D. Williamson, ORNL

Calculation of Coil-Associated Areas

- **Strongback behind coils**
  - $\text{area}_{back} = \text{area}_{coil} \times r_{mid,back}/\langle a_{coil}\rangle$ where $\text{area}_{coil} = L_{coil} \times \text{width}_{coil}$, $L_{coil} = 90R$, $\text{width}_{coil} = (R/10.03 - 0.02)$, $\langle a_{coil}\rangle = 0.504R$
    $r_{mid,back} = \langle a_{coil}\rangle + \text{depth}_{coil}/2 + \text{thick}_{sb}/2$

  for $\langle R\rangle = 8.25$ m, area = 263 m^2 vs 3(45 + 33.1) = 234 m^2 for D.W.

- **Shell between coils (outboard)**
  - $\text{area}_{shell} = (1 - 0.326) \times 0.67 \times [\text{area}_{coil\ winding\ surface} - \text{area}_{coil}] \times r_{mid,shell}/\langle a_{coil}\rangle$ where $\text{area}_{coil\ winding\ surface} = 27R^2$,
    $r_{mid,sb} = \langle a_{coil}\rangle + \text{depth}_{coil}/2 + \text{thick}_{sb} - \text{thick}_{shell}/2$

  for $\langle R\rangle = 8.25$ m, area = 913 m^2 vs 3(365.4) = 1096 m^2 for D.W.

- **Bucking cylinder (inboard)**
  - $\text{area}_{buck} = 0.326 \times \text{area}_{coil\ winding\ surface} \times r_{mid,buck}/\langle a_{coil}\rangle$
    $r_{mid,buck} = \langle a_{coil}\rangle + \text{depth}_{coil}/2 + \text{thick}_{buck}/2$ (+ thick_{back}??)

  for $\langle R\rangle = 8.25$ m, area = 765 m^2 vs 3(165.3) = 496 m^2 for D.W.

- **Values depend on model for structure thicknesses; area coverage fractions from D.Williamson's 3-D calcs**

Component Volumes Summary (m^3)

total modular coil volume	~~**154.05**~~	
conductor pack	77.02	
~~rest winding pack~~	~~77.02~~	
total structure volume	**404.35**	
bucking cylinder on inside	78.85	
strongback behind coils	270.69	
outer shell between coils	54.81	
total FW, blanket, BW volume		**398.891**
first wall	22.45	1.591
front full blanket	321.77	1.881
front blanket back wall	34.35	2.177
second blanket	0.00	2.202
transition blanket	20.32	1.765
total vacuum vessel volume	**299.68**	
full blanket vacuum vessel	259.13	2.933
shield-only vacuum vessel	12.60	2.424
transition vacuum vessel	27.95	2.689

r_{mid}(m) in blue

total shield + back wall volume	**218.78**	
ferritic steel shield	160.85	2.313
1st shield-only WC shield	6.01	1.705
shield-only back wall	1.69	1.825
2nd shield-only WC shield	15.80	2.057
1st transition WC shield	5.08	1.955
trans shield back wall	3.74	2.015
2nd transition WC shield	25.59	2.197
volume of manifolds	**302.77**	
full-blanket manifold	286.91	2.598
transition manifold	15.86	2.442
volume of empty core	**1778.51**	
volume of liquid metal in core	**342.91**	
volume of filled core	**2121.42**	

Composition
(Nominal Blanket/Shield and Shield-only zones)
(no divertor info)

Component	Thickness	Coverage Fraction	Composition
FW*	3.8 cm	100%	34% FS Structure 66% He Coolant
Blanket*	54.3 cm	85%#	79% LiPb (90% enriched Li) 7% SiC Inserts (95% d.f.) 6% FS Structure 8% He Coolant
Back Wall*	5 cm	100%	80% FS Structure 20% He Coolant
FS Shield	18 cm	85%	15% FS Structure 10% He Coolant 75% Borated Steel Filler
Manifolds	35 cm	85%	52% FS Structure 24% LiPb (90% enriched Li) 24% He Coolant ?% SiC Inserts ???
WC Shield-I* (shield-only zone)	17-21 cm	5%	88% WC Filler 5% FS Structure 7% He Coolant
WC Shield-II (shield-only zone)	38 cm	5%	15% FS Structure 10% He Coolant 75% WC Filler
VV	28 cm	100%	28% FS Structure 49% Water 23% Borated Steel Filler

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* Replaceable component.

\# For blanket and divertor,

Composition
(Transition Region)

Component	Av. Thickness	Coverage Fraction	Composition
FW*	3.8 cm		34% FS Structure 66% He Coolant
Blanket*	31 cm	10%	~79% LiPb (90% enriched Li) ~ 7% SiC Inserts ~ 6% FS Structure ~ 8% He Coolant
Back Wall*	5 cm		80% FS Structure 20% He Coolant
WC Shield-I*	7 cm	10%	88% WC Filler 5% FS Structure 7% He Coolant
WC Shield-II	28 cm	10%	15% FS Structure 10% He Coolant 75% WC Filler
Manifolds	17 cm	10%	52% FS Structure 24% LiPb (90% enriched Li) 24% He Coolant ?% SiC Inserts ???
VV	28 cm		28% FS Structure 49% **Water** 23% Borated Steel Filler

* Replaceable component.

Unit Cost and Mass Data for Systems Code

Designation	D1			
Description	LiPb Dual Coolant			
VV location	Internal to Coils	$/kg	kg/m3	$/kg
First Wall, Blanket	ODS/RA FS Li17Pb83(90%Li6) He	$103.00 $20.00	7800 8897	$83.85 $16.28
Local Shield	RAFS WC plates He	$103.00 $30.00	7800 15500	$83.85 $24.42
Shield	RAFS Borated FS Plates He	$78.00 $31.00	7800 7800	$63.50 $25.24
Vac Vessel	RAFS Borated FS Plates H_2O	$56.00 $31.00	7800 7800	$45.59 $25.24
		2004 $		1992 $

Other parameters

emultloc = 1.14

fwlife = 15 MW-yrs/m^2

thermeff = 0.42

fwth = 0.038

SiC inserts

$415.20/kg, 3200 kg/m^3

from option B chart

Component Thicknesses, Densities and Costs/m^3

nom. blanket + FS shield region 85%

blth1 = 0.542 m

blbw = 0.05 m

blth2 = 0

blgap = 0

FSshth = 0.18 m

thman1 = 0.35 m

shvvgap = 0.02 m

vvth1 = 0.28 m

densities in tonnes/m^3, cost in k\$/m^3

fwthden = 7.8*0.34 = 2.652 tonnes/m^3

blth1den = 7.8*0.06 + 15.5*0.07 = 1.553 tonnes/m^3

blbwden = 7.8*0.8 = 6.24 tonnes/m^3

thmanden = 7.8*0.52 = 4.056 tonnes/m^3

FSshthden = 7.8*0.15 + 7.8*0.75 = 7.02 tonnes/m^3

vvth1den = 7.8*0.28 + 7.8*0.23 = 3.978 tonnes/m^3

fwthcpm3 = 7.8*0.34*103. = 222.376

blth1cpm3 = 7.8*0.06*103. + 15.5*0.07*30. = 65.742

blbwcpm3 = 7.8*0.8*103. = 523.24

FSshthcpm3 = 7.8*0.15*78. + 7.8*0.75*31. = 222.694

thmancpm3 = 7.8*0.52*78. = 257.555

vvth1cpm3 = 7.8*0.28*56. + 7.8*0.23*31. = 177.918

transition region 10%

blth3 = 0.31 m

WCshth3 = 0.07 m

WCshth4 = 0.28 m

thman2 = 0.35/2 = 0.175 m

WCshth3den = 7.8*0.05 + 15.5*0.88 = 14.03 m

WCshth4den = 7.8*0.15 + 15.5*0.75 = 12.975 m

WC shield only region 5%

WCshth1 = 0.19 m

shbw = 0.05

shgap = 0

WCshth2 = 0.38 m

vvth2 = 0.28 m

WCshth1den = 7.8*0.05 + 15.5*0.88 = 14.03

shbwden = 7.8*0.8 = 6.24

WCshth2den = 7.8*0.15 + 15.5*0.75 = 12.795

vvth2den = vvth1den

WCshth1cpm3 = 7.8*0.05*103. + 15.5*0.88*30. = 449.37

shbwcpm3 = 7.8*0.8*103. = 642.72

WCshth2cpm3 = 7.8*0.15*103. + 15.5*0.75*30 = 469.26

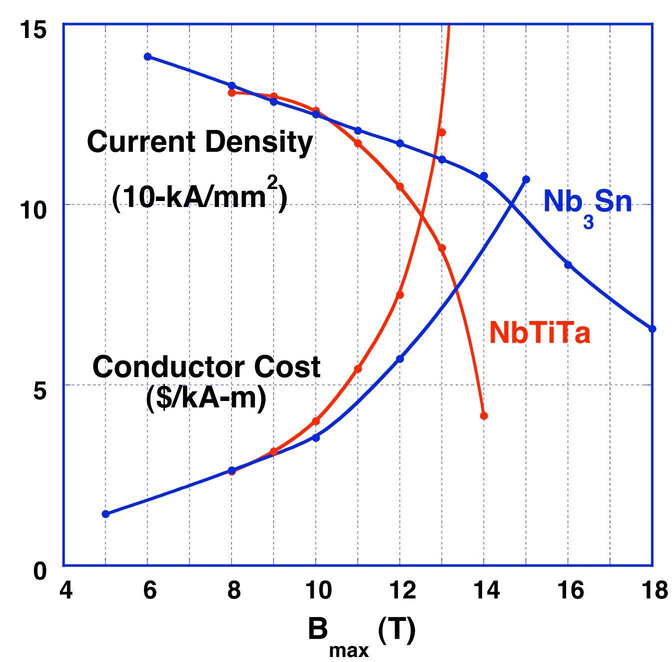
vvth2cpm3 = vvth1cpm3

Calculation of Coil-Related Costs (Bromberg)

- **Conductor cost varies rapidly with B_{max}**
  * cost = $L_{coil} I_{coil} f(B_{max}) = k_1 k_2 B_{axis} \langle R \rangle^2 f(B_{max})$
  * could be reduced factor of 3 by developing advanced manufacturing and increased billet size?

- **Cost of winding coil: mass of conductor x \$80/kg**
  * cost = $80\rho L_{coil} I_{coil}/j = k_1 k_2 B_{axis} \langle R \rangle^2 [80\rho/j(B_{max})]$

- **Coil structure cost = volume x 7800 kg/m^3 x \$56/kg = $k_3 \langle R \rangle^2$**



Component Mass Summary (tonnes)

total modular coil mass	~~847.27~~
conductor pack	423.64
~~rest winding pack~~	~~423.64~~
total VF coils	0.00
divertor coils	0.00
total structure mass	**3153.91**
bucking cylinder	614.99
strongback	2111.42
outer shell	427.49
total blanket, first, back wall	**805.16**
first wall	59.54
front full blanket	499.71
front blanket back	214.37
second blanket	0.00
transition blanket	31.55
total vacuum vessel mass	**1192.13**
full blanket vacuum vessel	1030.81
shield-only vacuum vessel	50.12
transition vacuum vessel	111.20

shield and back wall masses	**1825.06**
ferritic steel shield	1129.16
1st shield-only WC shield	84.38
shield-only back wall	10.57
2nd shield-only WC shield	202.17
1st transition WC shield	71.29
trans shield back wall	23.34
2nd transition WC shield	327.49
mass of manifolds	**1228.05**
full blanket manifold	1163.71
transition manifold	64.34
total nuclear island	**9051.58**
mass of liquid metal coolant	**3050.89**
mass of nuclear island + coolant	**12,102.47**

Comparing Masses with AT, RS & SPPS

Mass (tonnes)	CS	AT	RS	SPPS
FW/Blanket/BW	805	255	585	251
Shield, BW, man.	3053	882	4235	9453
Coils	847	1525	3280	4191
Structure	3154	----	1627	5365
Vacuum Vessel	1192	1415	1357	2171
Fusion Power Core	9,052	5,226	12,679	21,430
LM Coolant	3,051	5,269	223	175
FPC + Coolant	12,102	10,495	12,902	21,605

Component Cost Summary (1992 $)

total modular coil cost	**73.27**
conductor pack	60.21
rest winding pack	13.80
total VF coils	0.00
divertor coils	0.00
total structure cost	**143.79**
bucking cylinder	28.04
strongback	96.26
outer shell	19.49
total blanket, first, back wall	**45.46**
first wall	4.99
front full blanket	21.15
front blanket back	17.98
second blanket	0.00
transition blanket	1.34
total vacuum vessel cost	**43.41**
full blanket vacuum vessel	37.53
shield-only vacuum vessel	1.82
transition vacuum vessel	4.05

shield and back wall costs	**58.41**
ferritic steel shield	35.70
1st shield-only WC shield	2.20
shield-only back wall	0.89
2nd shield-only WC shield	6.03
1st transition WC shield	1.87
trans shield back wall	1.95
2nd transition WC shield	9.78
cost of manifolds	**77.98**
full blanket manifold	73.90
transition manifold	4.09
total nuclear island	**299.27**
cost of liquid metal coolant	**126.68**
cost of nuclear island + coolant	**425.94**

Cost Accounts (1992 M$)

Cost 20 (Land) = 10.439

Cost 21.1 (site improvements) = 18.440
Cost 21.2 (reactor building) = 127.615
Cost 21.3 (turbine building) = 31.748
Cost 21.4 (cooling system) = 7.903
Cost 21.5 (PS building) = 9.988
Cost 21.6 (misc. buildings) = 112.591
Cost 21.7 (vent. stack) = 1.973
Cost 21 (Structure) = 325.421

Cost 22.1.1.1 (FW) 4.992
Cost 22.1.1.3 (BL+ BW) 40.465
Cost 22.1.1 (Bl, BW & 1st wall) 45.458
Cost 22.1.2 (Shield + BW) = 136.397
Cost 22.1.3 mod. coils 74.004
Cost 22.1.3 VF coils 0.000
Cost 22.1.3 div = 0.000
Cost 22.1.3 structure = 143.788
Cost 22.1.3 (total coils) = 74.0041

Cost 22.1.4 (Heating) = 53.662
Cost 22.1.5 (Primary Str.) = 143.788
Cost 22.1.6 (Vac. Sys.) = 109.232
Cost 22.1.7 (Power Sup.) = 55.322
Cost 22.1.8 (Imp. Control) = 5.528
Cost 22.1.9 (Dir. Ener. Conv.) 0.000
Cost 22.1.10 (ECH) = 0.000
Cost 22.1 (Core) = 623.391

Cost 22.2.1 prim. coolant 196.978
Cost 22.2.2 interm coolant 0.000
Cost 22.2.3 sec. coolant 0.000
Cost 22.2 (Heat transport) = 196.978

Cost 22.3 aux. cooling 2.699
Cost 22.4 rad. waste = 4.810
Cost 22.5.1 fuel inj. = 11.411
Cost 22.5.2 fuel proc. 13.395
Cost 22.5.3 fuel storag 5.706
Cost 22.5.4 atm T recov 2.707
Cost 22.5.5 H2O T recov 5.706
Cost 22.5.6 BL T recov. 5.706
Cost 22.5 fuel hand. = 44.630
Cost 22.6 other pl eq = 43.882
Cost 22.7 I&C = 35.975
Cost 22 (Reactor Plant) = 971.413

Cost 23.1 turb.-gen. = 0.000
Cost 23.2 misc turb-gen 0.000
Cost 23.3 heat reject. 41.508
Cost 23.4 condens. sys 0.000
Cost 23.5 feed heating 0.000
Cost 23.6 other turb eq 0.000
Cost 23.7 I&C equip. = 0.000
Cost 23 (Turbine Plant) = 262.540

Cost 24.1 = 0.000
Cost 24.2 = 0.000
Cost 24.3 = 0.000
Cost 24.4 = 0.000
Cost 24.5 = 0.000
Cost 24.6 = 0.000
Cost 24.7 = 0.000
Cost 24 (Electric Plant) = 103.624

Cost 25.1 = 0.000
Cost 25.2 = 0.000
Cost 25.3 = 0.000
Cost 25.4 = 0.000
Cost 25 (Misc. Plant Eq.) = 51.916

Cost 26.4 other mater. 124.097
Cost 26 (Spec. Matls.) = 126.672

Comparison of General Plant Costs (1992 $)

Parameter	CS	AT	RS	SPPS
$\langle R \rangle$, m	6.93	5.20	5.52	13.95
$\langle B_{axis} \rangle$, T	6.28	5.86	7.98	4.94
$\langle \beta \rangle$, %	5.0	9.2	5.0	5.0
FPC Mass, tonnes	9,052	5,226	12,679	21,430
CoE, mills/kW$_e$h (1992 $)	55.7	56.6	75.7	74.9
90 Total Direct Cost (M$)	1902	1757	2189	2261
20 Land	10.4	10.6	10.4	10.4
21 Structure	325.4	335.5	331.0	332.5
22 Reactor Plant Equip.	*971.4*	*900.3*	*1386*	*1487*
23 Turbine Plant Equip.	262.5	243.0	284.4	254.0
24 Electric Plant Equip.	103.6	110.3	110.6	103.6
25 Misc. Plant Equip.	51.9	50.1	56.2	51.9
26 Special Materials	126.7	83.8	11.1	21.1
Heat Rejection System		+23.3		
22+26 Reactor Plant + LM	1098	984.1	1397	1508

- **Only Reactor Plant Equip. contains stellarator costs**

Comparison of General Plant Costs (1992 $)

Cost (M$)	CS	AT	RS	SPPS
21 Structure	325.4	335.5	331.0	332.5
21.2 reactor building	127.6	n. a.	n. a.	141.6
21.6 misc. buildings	112.6	n. a.	n. a.	112.7
22 Reactor Plant Equip.	971.4	900.3	1386	1487
22.1 reactor equipment	*623.4*	*519.9*	*966.4*	*1115*
22.2 heat transport	197.0	209.9	258.3	217.8

- **While the reactor equipment is the largest cost component, the costs of structure (buildings) and heat transport are also large**

Comparing Costs with AT, RS & SPPS

Cost (M$)	CS	AT	RS	SPPS
22.1 Reactor Equipment	623.4	519.9	966.4	1115
Cost of stellarator parts	255.9 41%	274.9 53%	516.3 53%	750.9 67%
22.1.1 blanket & 1st wall	45.5	67.9	74.3	71.5
22.1.2 shield, BW, man.	136.4	73.3	168.0	289.8
22.1.3 coils	74.0	133.7	274.0	389.6
22.1.4 heating	53.7	41.0	164.2	54.2
22.1.5 primary structure	143.8	29.8	53.4	152.9
22.1.6 vacuum systems	109.2	109.2	159.2	85.4
22.1.7 power supplies	55.3	56.1	55.3	55.3
22.1.8 impurity control	5.5	4.5	13.6	12.0
22.1.10 ECH startup	0	4.4	4.3	4.3

Cost Element Breakdown (1992 M$)

	NCSX-ARE	ARIES-RS	ARIES-AT	
Cost 20 (Land)	10.439	10.438	10.589	constant
Cost 21.1 (site improvements)	18.440			constant
Cost 21.2 (reactor building)	127.615			$\sim V_{\text{reactor building}}^{0.62}$
Cost 21.3 (turbine building)	31.748			$\sim[(\eta_{th}P_{th})^{0.75} + \text{constant}]$
Cost 21.4 (cooling system)	7.903			$\sim(\eta_{th}P_{th})^{0.3}$
Cost 21.5 (PS building)	9.988			constant
Cost 21.6 (misc. buildings)	112.591			constant
Cost 21.7 (vent. stack)	1.973			constant
Cost 21 (Structure)	325.421	331.027	335.497	
Net thermal efficiency η_{th}	42%	XX%	XX%	
Global energy multiplier (gloem)	XXXX	XXXX	XXXX	
$P_{th} = P_n \times \text{gloem} + P_\alpha$	2610.2	2618.6	1982.4	
Gross Electric Power (MW)	1054.9	1204.5	1169.6	

Cost Element Breakdown (1992 M$)

	NCSX-ARE	ARIES-RS	ARIES-AT	
Cost 22.1.1.1 (FW)	4.992			
Cost 22.1.1.3 (BL + BW)	40.465			
Cost 22.1.1 (Bl/BW & 1st wl.)	45.458	74.263	67.851	
Cost 22.1.2 (Sh/BW/man)	136.397	168.010	73.265	
Cost 22.1.3 mod coils	74.004			
Cost 22.1.3 VF coils	0.000			
Cost 22.1.3 divertor	0.000			
Cost 22.1.3 (coils + str)	198.160	274.014	133.724	
Cost 22.1.4 (Heating)	53.662	164.211	40.984	constant 20 MW
Cost 22.1.5 (Primary Str.)	143.788	53.449	29.785	coil winding surface
Cost 22.1.6 (Vac. Sys.)	109.232	159.226	109.231	vacuum vessel only
Cost 22.1.7 (Power Sup.)	55.322	55.322	56.119	constant
Cost 22.1.8 (Imp. Control)	55.278	13.610	4.528	~ divertor area
Cost 22.1.9 (Dir. Ener. Conv.	0			
Cost 22.1.10 (ECH breakdown)	0	4.334	4.396	
Cost 22.1 (Core) =	623.391	966.439	519.883	

Cost Element Breakdown

	NCSX-ARE	ARIES-RS	ARIES-AT	
Cost 22.2.1 primary coolant	196.978			$\sim P_{th}^{0.55}$
Cost 22.2.2 intermediate coolant	0.000			
Cost 22.2.3 secondary coolant	0.000			
Cost 22.2 (Heat transport)	196.978	258.267	209.947	
Cost 22.3 aux. cooling	2.699			$\sim P_{th}$
Cost 22.4 rad. waste	4.810			$\sim P_{th}$
Cost 22.5.1 fuel injection	11.411			constant
Cost 22.5.2 fuel processing	13.395			constant
Cost 22.5.3 fuel storage	5.706			constant
Cost 22.5.4 atm T recover.	2.707			constant
Cost 22.5.5 H_2O T recover.	5.706			constant
Cost 22.5.6 BL T recover.	5.706			constant
Cost 22.5 fuel handling	44.630			constant
Cost 22.6 other plant equip	43.882			$\sim P_{th}$
Cost 22.7 I&C	35.975			constant
Cost 22 (Reactor Plant)	971.413	1385.691	900.282	

Cost Element Breakdown

	NCSX-ARE	ARIES-RS	ARIES-AT	
Cost 23 (Turbine Plant)	262.540	284.446	243.034	$\sim[(\eta_{th}P_{th})^{0.83}$ + constant]
23.3/26 heat reject.	41.508		23.317	$\sim[P_{th} - (\eta_{th}P_{th})]$
Cost 24 (Electric Plant)	103.624	110.604	110.326	$\sim(\eta_{th}P_{th})^{0.49}$
Cost 25 (Misc. Plant Eq.)	51.916	56.165	50.139	$\sim(\eta_{th}P_{th})^{0.59}$
26.4 other materials	192.011			$\sim V_{LiPb}$
Cost 26/7 (Spec. Matls.)	126.672	11.073	83.766	
Cost 90 (Direct Cost)	1843.069	2189.445	1756.949	

Total Costs (1992 M$) and COE

Cost 90	Total Dir Cost	1843.069	51.827%
Cost 91	Construction	221.168	6.219
Cost 92	Home office	95.840	2.695
Cost 93	Field office	110.584	3.110
Cost 94	Owner's costs	340.600	9.578
Cost 96	Proj. Contingency	440.678	12.392
Cost 97	Constr Interest	504.264	14.180
Cost 98	Constr Escalation	0.000	0.000
Cost 99	Total Capital Cost	3556.203	100.000

[90]	Unit direct cost, UDC	1843.069
[94]	Unit base cost, UBC	3051.939
[99]	Unit total cost, UTC	3556.203

Capital return	46.136
[40-47,51] O&M costs	8.177
[50] FW/BL/WCSHI/BW replace	0.883
Decomissioning allowance	0.500
[02] Deuterium fuel	0.030
Cost of Electricity, COE	55.726 in 1992 $

cost of replacement blanket + shield 52.360

number of blanket + shield replacements 14.35

CoE Components for CS, AT, RS & SPPS

mills/kW$_e$h	CS	AT	RS	SPPS
CoE (in 1992 $)	55.73	56.61	75.66	74.92
Cap. Return	46.14	43.95	61.34	63.34
O & M	8.18	8.34	9.16	9.16
FW/BI replace.	0.88	3.79	4.63	1.90
Decomm.	0.50	0.50	0.50	0.50
Fuel costs	0.03	0.03	0.03	0.03

- Largest CoE component is Capital Return
- Cap. Return α Total Cap. Cost α Total Direct Cost