Progress on Systems Code

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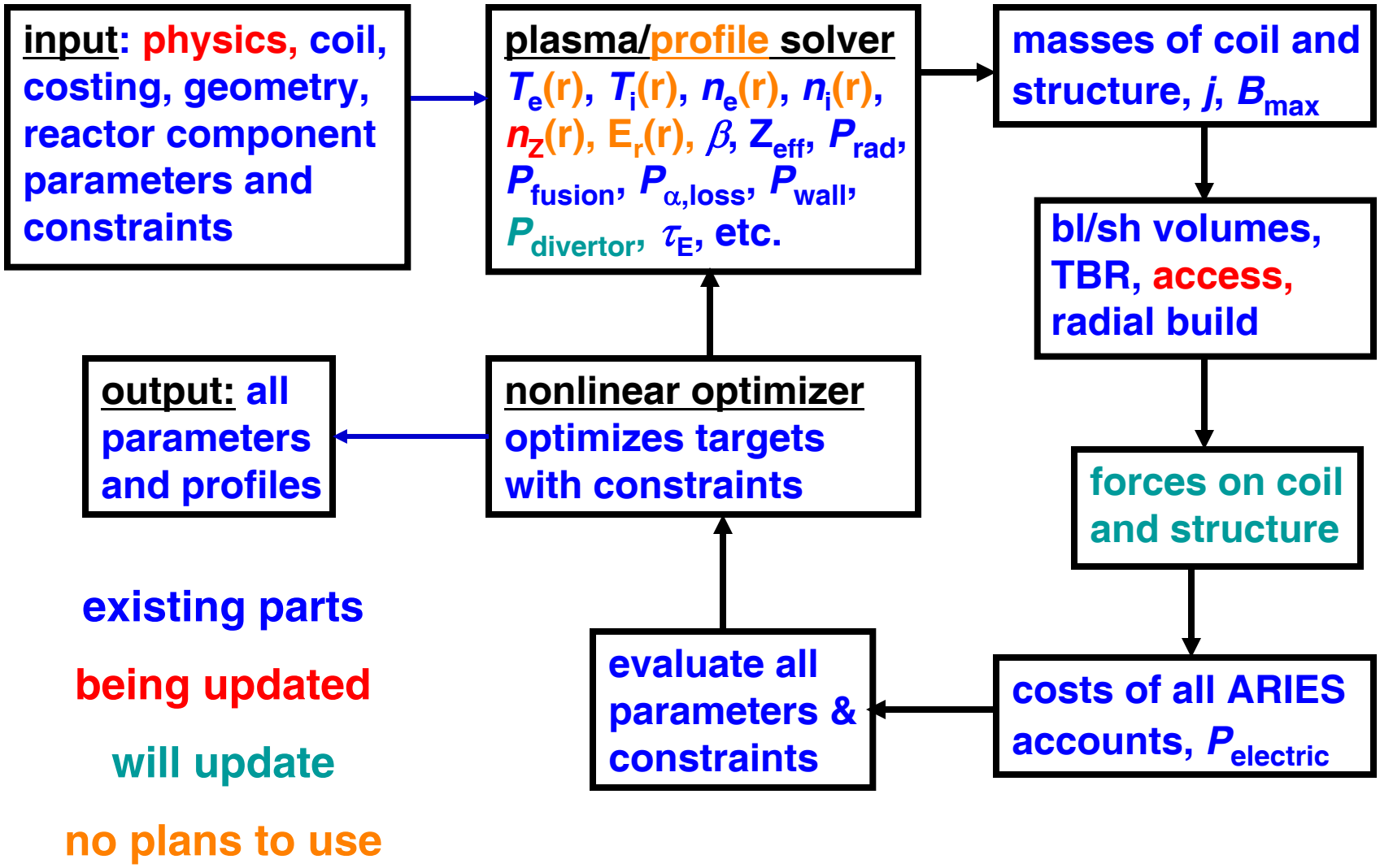
Systems Optimization Code

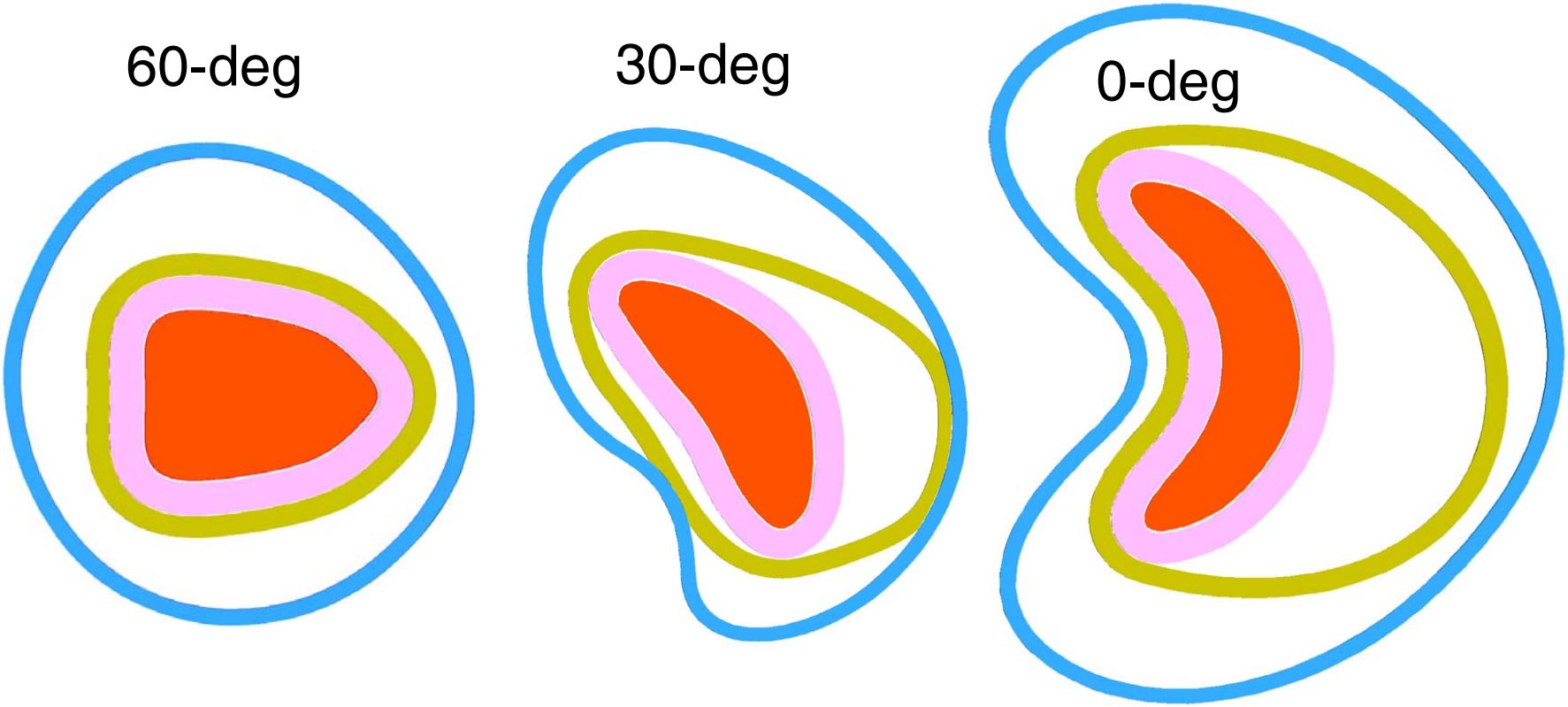
- Minimizes core cost or size or CoE with constraints for a given plasma and coil geometry using a nonlinear constrained optimizer
- Iterates on a number of optimization variables
  - plasma: $\langle T_i \rangle$, $\langle n_e \rangle$, conf. multiplier; coils: width/depth of coils
  - reactor variables: B_0, $\langle R \rangle$
- Large number of constraints allowed (=, <, or >)
  - $P_{electric}$, ignition margin, β limit, confinement multiplier, radial build, coil j and B_{max}, plasma-coil distance, clearance between coils, blanket/shield thicknesses, TBR, coil-coil access
- Large number of fixed parameters for plasma and coil configuration, plasma profiles, transport model, cost component algorithms, and engineering parameters

MHHOPT Reactor Optimization Code



Geometry

- **Only looked at port maintenance approach**
  - **small non-angular-dependent gap between blankets, shields, vacuum vessel (like at 60-deg cross section)**



Systems Code Output

- **Plasma parameters and profiles**
  - $\langle R \rangle$, $\langle B_{axis} \rangle$, W_{plasma}, τ_E, H factors, $\langle \beta \rangle$, β^*, n_{Fe}/n_e, n_O/n_e, Z_{eff}
  - $\langle T \rangle$, T_{i0}, $\langle n \rangle$, n_{i0}, n_{e0}, $\langle n \rangle / n_{Sudo}$, n_{DT}/n_e
  - ignition margin, P_{fusion}, $P_{electric}$, $P_{neutron}$, $P_{charged}$, $P_{divertor}$, components of P_{rad}, P_{wall}, P_{loss}
- **Coil parameters**
  - modular & VF coil dimensions, currents, j, B_{max}
- **Reactor parameters**
  - blanket and shield thicknesses, gaps, access between coils
- **All ARIES cost accounts in 2004$**
  - includes total direct cost, total capital cost, cost of electricity
- **All component masses & mass utilization**

Approach and Assumptions

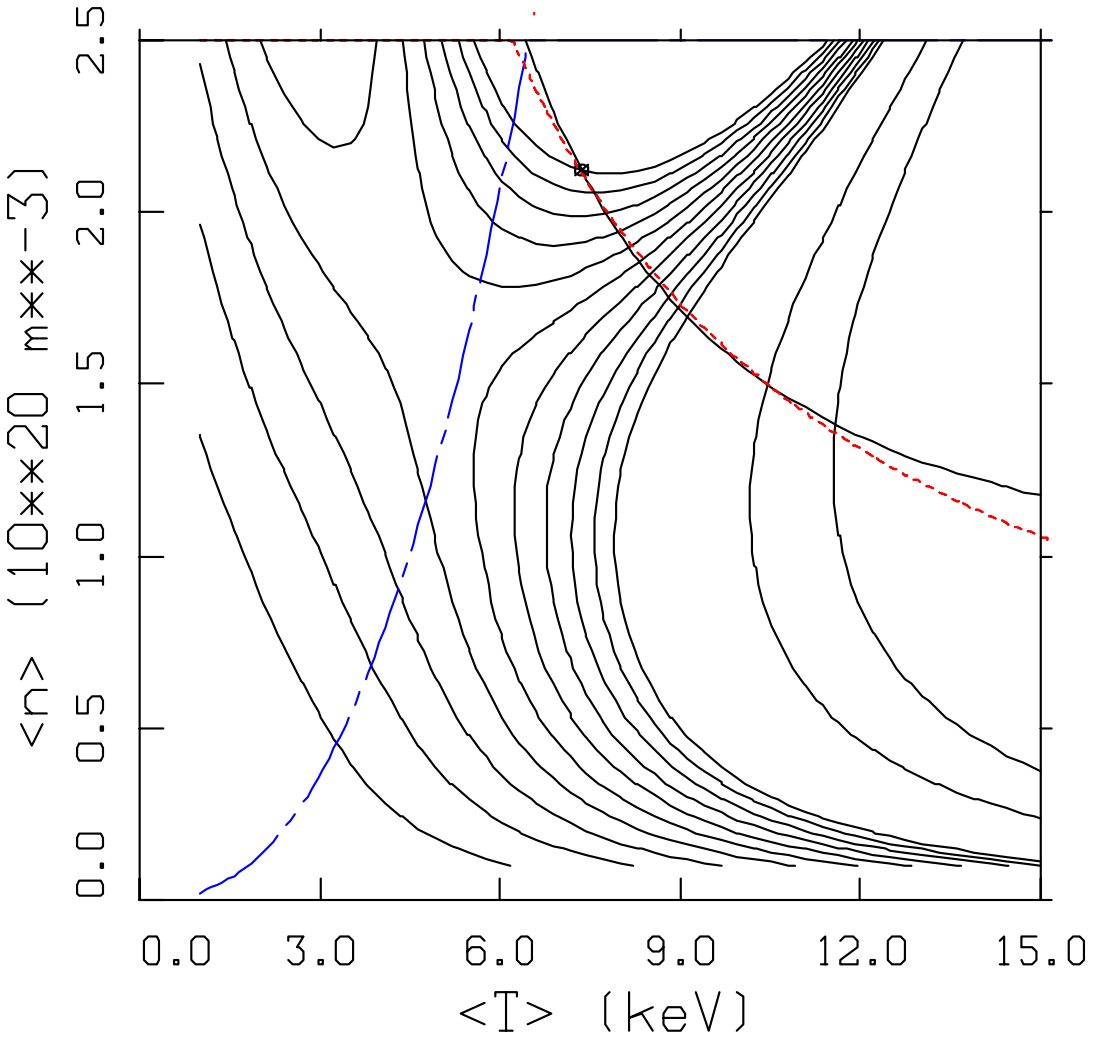
- 2004 costs for blanket/shield/vacuum vessel from Les and for coils from Leslie
- Inflation factor from 1980 for other costs
- Geometry factors for blankets, shields, vacuum vessel and coils from Long-Poe
- Five blanket/shield models from Laila
  - two blanket/shield areas (with fraction), no transition area yet
  - $<p_{wall}>$ limit and shield thickness the same for all blanket/shield cases so far
- Checking costing algorithms against ARIES-AT, ARIES-RS and SPPS results
  - currently only valid for LSA = 2 and 1
- Compared results against 1-D POPCON calculations

Good Agreement Between Codes

NCSX-1, <R> = 8.56

<B> = 4.53, H = 1.904

Systems	POPCON
$P_{\alpha,\,MW}$ 396	399
$\langle n_{20}\rangle$ 2.13	2.12
$\langle T_k\rangle$ 7.31	7.35
$\langle \beta_{\%}\rangle$ 6.00	6.02
%He 3.74	3.76



Systems Code Status/Caveats

- **Costing algorithms**
  - some ~20% disagreements in comparing with previous ARIES cases but doesn't affect relative comparisons or trends
  - coil case thicknesses not calculated from forces yet
  - a few (small) cost accounts not finished yet
- **Optimization logic bug**
  - minimizing capital cost uses COE instead
  - minimizing <*R*> leads to strange results
- **Comparison with POPCON code results**
  - same plasma parameters obtained for the operating point
- **Currently in adding features and debug cycle**

$\Rightarrow$ Values (<*R*>, <*B*>, Cost of Electricity, etc.) are not correct, but relative values should be correct

Different Blanket/Shield Cases

	$\langle B_{axis} \rangle$ (T)	CoE	H-LG	Gap/Δ
Flibe/FS/Be H_20 int VV	**4.56**	**75.8**	**2.04**	**0.20**
LiPb/SiC H_20 int VV	**4.28**	**79.0**	**2.10**	**0.18**
LiPb/FS/He H_20 int VV	**4.53**	**76.6**	**1.89**	**0.15**
LiPb/FS/He He ext. vv	**4.53**	**83.5**	**1.89**	**0.15**
LiPb/FS/He/H_2O He ext vv	**4.53**	**73.8**	**1.89**	**0.13**
LiPb/FS/He H_20 int VV, LSA = 1	4.94	64.4	2.02	0.15

- **NCSX-1, LSA = 2, LiPb/FS/He H_2O-cooled int. vacuum vessel**
- **Optimization: $\langle R \rangle$ = 8.56 m, $\langle p_{wall} \rangle$ = 3.0 MW/m^2, B_{max} = 16 T**
- **Small difference in CoE for internal vacuum cases, somewhat larger range 73.8–83.5 for external vacuum vessel cases**

Values for Different Configurations

	NCSX-1	NCSX-2	MHH2-8	MHH2-16
$\langle p_{wall} \rangle$, MW/m^2	3.0	2.08	1.66	3.0
$\langle R \rangle$ (m)	8.56	10.22	8.91	7.59
$\langle B_{axis} \rangle$ (T)	4.53	3.95	4.05	3.82
H-LG	1.89	1.94	2.43	1.96
CoE	76.6	89.0	79.5	71.7
gap/Δ	0.15	0	0	0.03

- LSA = 2, LiPb/FS/He H_2O-cooled int. vacuum vessel
- Large range in CoE: 71.7–89.0

Typical Code Summary

MHHOPTNEW code KU81

LiPb/FS/He H2O-cooled int. vacuum vessel

inflation factor	2.0081
safety assurance flag	2

following CONSTRAINTS were selected:

ignition margin	1.00
volume averaged beta	0.06
radial build	
magnetic field at coil	16.00
ave. neutron wall load	3.00
maximum density	
Electric Power (GW)	1.00
Confinement multiplier	6.00

VARIABLES selected for iteration

major radius	5.00	20.00
field on axis	3.00	10.00
ion density	0.50	10.00
ion temperature	1.00	50.00
coil width	0.010	5.00
confinement multiplier	0.10	9.00

FIGURE OF MERIT .....

76.6441 Cost of Electricity

FINAL VALUES OF CONSTRAINTS:

ignition margin	0.9998
volume averaged beta (%)	6.00
radial build margin	0.85
magnetic field at coil (T)	16.00
ave. neutron wall load (MW/m2)	3.00
maximum density (10**20 m-3)	2.85
Electric Power (GW)	1.00
ratio of tauE to conf. multiplier	1.89

FINAL DESIGN

major radius (m)	8.559
field on axis (T)	4.528
vol avg den (10**20 m-3)	2.130
density averaged temp (keV)	7.309
coil dimensions (m x m)	0.43 x 0.83
current density (MA/m2)	33.09

Typical Code Summary

Plasma Parameters

central ion temp (keV)	12.791	
cen ion density (10**20 m-3)	4.101	
cen el. density (10**20 m-3)	4.260	
line avg den. (10**20 m-3)	2.840	
max el. density (10**20 m-3)	2.854	
fraction fuel to electrons	0.925	
confinement time, taue (sec)	1.133	
corrected taue, (sec)	1.354	
stored plasma energy (MJ)	448.68	
volume averaged beta (%)	6.000	
beta star (%)	8.563	
fraction carbon impurity	0.000	%
fraction iron impurity	0.0000	%
fraction helium	3.74	%
z effective	1.075	

ignition margin	1.000	
net electric power (MW)	1000.000	
gross electric power (MW)	1000.000	
fusion power (MW)	1984.027	
thermal power (MW)	2222.222	
heating power (MW)	396.059	
absorbed power (MW)	0.000	
D-T Fusion power	396.059	MW
D-D Fusion power	0.000	MW
power in neutrons	1587.968	MW
power in charged particles	396.059	MW
divertor power	331.336	MW
radiated power	64.723	MW
fuel bremsstrahlung	63.846	MW
carbon bremsstrahlung	0.000	MW
iron bremsstrahlung	0.000	MW
synchrotron radiation	0.877	MW
conduction power	331.419	MW
fusion power to plasma	396.059	MW
fraction alpha power	100.000	%
radiated power fraction	16.342	%
neutron wall load (MW/m2)	3.000	
radiated wall load (MW/m2)	0.075	

Typical Cost Summary

COST SUMMARY (M$)			% of 99	% of 22.1
20	Land	12.822	0.258	
21	Structure	326.933	6.582	
22.1.1	Bl. & 1st wl.	128.306	2.583	14.247
22.1.2	Shield	119.425	2.404	13.261
22.1.3	Magnets	346.233	6.970	38.447
22.1.4	Supp. Heating	65.915	1.327	7.319
22.1.5	Primary Str.	73.326	1.476	8.142
22.1.6	Reactor Vac. S	90.115	1.814	10.007
22.1.7	Pow Supply	67.954	1.368	7.546
22.1.8	Impurity Cont	9.277	0.187	1.030
22.1.9	Direct E. Conv	0.000	0.000	0.000
22.1.1	ECH breakdown	0.000	0.000	0.000
22.1	Total	900.551	18.129	100.00
22.2	Heat transport	221.461	4.458	
22	Reactor Plant	1329.003	26.754	
23	Turbine Plant	299.621	6.032	
24	Electric Plant	125.473	2.526	
25	Misc. Plant Eq	61.793	1.244	
26	Special Material	0.781	0.016	

Typical Cost Summary

Cost 90	Total Dir Cost	2156.425	43.412	percentages
Cost 91	Construction	258.771	5.209	of total
Cost 92	Home office	112.134	2.257	
Cost 93	Field office	129.386	2.605	
Cost 94	Owner's costs	490.961	9.884	
Cost 96	Proj. Contingency	752.610	15.151	
Cost 97	Constr Interest	1067.119	21.482	
Cost 98	Constr Escalation	0.000	0.000	
Cost 99	Total Capital	4967.405	100.000	

[90]	Unit direct cost, UDC	2156.425
[94]	Unit base cost, UBC	3900.287
[99]	Unit total cost, UTC	4967.405
	Capital return	64.444
[40-47,51]	O&M costs	10.045
[50]	B/FW replacement	1.763
	Decomissioning allow.	0.363
[02]	Deuterium fuel	0.03

Cost of Electricity, COE 76.644 in 2004$, 62.396 in 1992$

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Typical Mass Summary

MASS SUMMARY	(tonnes)	
total hf coil mass	3136.71	
total vf coil mass	0.00	
total coil mass	3136.71	
bucking cyl mass	0.00	
shield mass	1608.95	
total blanket, reflector, wall	2561.74	
total structure mass	1.39	
total nuclear island	7246.61	
mass utilization efficiency, kwe/tonne		137.996

Cost Element Breakdown

COST COMPONENTS .....

Cost 20 (Land) =	**12.822**
Cost 21.1 (site improvements) =	**22.651**
Cost 21.2 (reactor building) =	**138.474**
Cost 21.3 (turbine building) =	**25.287**
Cost 21.4 (cooling system) =	**9.597**
Cost 21.5 (PS building) =	**12.324**
Cost 21.6 (misc. buildings) =	**109.754**
Cost 21.7 (vent. stack) =	**2.435**
Cost 21 (Structure) =	**326.933**

Cost Element Breakdown

COST COMPONENTS

Cost 22.1.1.1 (FW)	12.219	
Cost 22.1.1.3 (BL)	116.087	
Cost 22.1.1 (Bl. & 1st wl.)	128.306	14.247%
Cost 22.1.2 (Shield)	119.425	13.261%
Cost 22.1.3 mod. coils	346.233	
Cost 22.1.3 VF coils	0.000	
Cost 22.1.3 divertor	0.000	
Cost 22.1.3 (coils) =	346.233	38.447%
Cost 22.1.4 (Heating)	65.915	
Cost 22.1.5 (Primary Str.)	73.326	
Cost 22.1.6 (Vac. Sys.)	90.115	
Cost 22.1.7 (Power Sup.)	67.954	
Cost 22.1.8 (Imp. Control)	9.277	
Cost 22.1.9 (Dir. Ener. Conv.	0.000	
Cost 22.1.10 (ECH) =	0.000	
Cost 22.1 (Core) =	900.551	

Cost Element Breakdown

Cost 22.2.1 prim. coolant	221.461
Cost 22.2.2 interm. coolant	0.000
Cost 22.2.3 sec. coolant	0.000
Cost 22.2 (Heat transport)	221.461
Cost 22.3 aux. cooling	2.810
Cost 22.4 rad. waste	5.076
Cost 22.5.1 fuel injection	14.002
Cost 22.5.2 fuel processing	16.453
Cost 22.5.3 fuel storage	7.001
Cost 22.5.4 atm T recover.	3.325
Cost 22.5.5 H2O T recover.	7.001
Cost 22.5.6 BL T recover.	7.001
Cost 22.5 fuel handling	54.784
Cost 22.6 other plant equip	45.890
Cost 22.7 I&C	44.189
Cost 22 (Reactor Plant)	1329.003

Cost Element Breakdown

Cost 23 (Turbine Plant)	299.621
Cost 24 (Electric Plant)	125.473
Cost 25 (Misc. Plant Eq.)	61.793
Cost 26.4 other materials	0.502
Cost 26.5 Ar gas cover	0.264
Cost 26 (Spec. Matls.)	0.781

Steps Needed to Complete Optimization/Systems Code Analysis

- **Blanket/shield refinements**
  - transition region
  - case-dependent $\langle p_{wall} \rangle$ limits and ln(p_{wall}) shield thicknesses
- **Costing algorithms**
  - resolve differences comparing with previous ARIES values
  - calculate coil case thicknesses from forces
  - complete few remaining cost accounts
  - add any new features requested at this meeting
- **Optimization logic**
  - determine why minimizing capital cost uses COE instead and minimizing $\langle R \rangle$ leads to strange results
  - update impurity treatment
- **Finish addition/debug cycle; modify summary?**

Questions

- **What new features should I add to my optimization/ systems code output?**
  - **what features in ASC output were important?**
  - **need same format as other ARIES summaries where applicable? (stellarator parameters differ from tokamak parameters)**
- **Costing algorithms**
  - **want costs in 1992 or 2004 values? both?**
  - **using LSA = 2, want LSA = 1 values? other LSA values??**
  - **include liquid coolants in blanket/shield masses?**

Summary

- Added geometry for blankets, shields, vacuum vessel and coils for four plasma/coil configurations
- Added five blanket/shield models
- Added LSA = 2 and 1 in costing algorithms
- Checking costing algorithms against ARIES-AT, ARIES-RS and SPPS results
- Compared results against 1-D POPCON calculations
- Identified work needed to complete optimization/ systems code analysis