An Advanced Computational Algorithm for Systems Analysis of TOKAMAK Power Plants

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Overview of Today's Presentation

- Purpose:
  - To present the Fusion Engineering and Design Paper on ARIES Systems Code
  - To discuss the best results that demonstrate the code capabilities.
- Timing:
  - Overview of the systems code and comprising algorithms – 30 min.
  - Overview of results and selection of representative cases. – 30 min.
  - General discussion of code approach and results. – 30 min.

Fusion Engineering and Design Paper Outline

- **Goal: to introduce the ARIES systems code to the fusion science community with a detailed, well referenced manuscript.**

ARIES Systems Code Algorithm - Motivation

- A new ARIES systems code is introduced in order to achieve the following objectives:
  – Develop and integrate state-of-art physics, engineering and costing algorithms.
  – Create an operational design space in form of a large database of viable operating points that span over a wide range of physics and engineering parameters.
  – Explore this database by modern data analysis techniques in order to highlight tradeoffs or parameters that are difficult to achieve but may yield a highly attractive power plant.
- The focus is on computational efficiency, credible physics and engineering algorithms that can simulate both advanced and near-term solutions and on “easy to build” modular approach.

ARIES Systems Code Algorithm - Structure

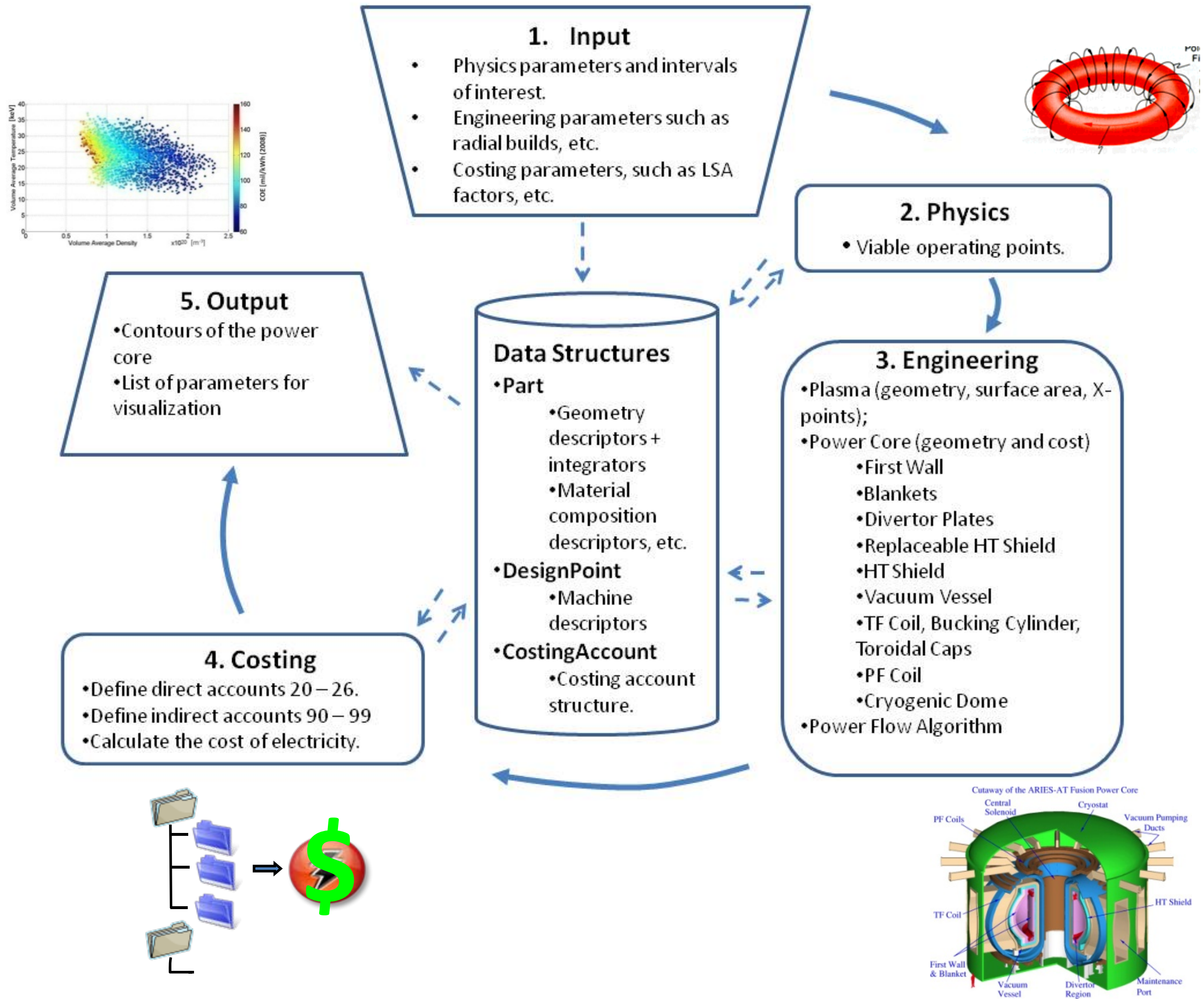
- ARIES systems code consists of three modules, which are physics, engineering and costing.
  - Physics Module
    - Originally developed in order to examine high field compact tokamak burning plasmas for FIRE project.
    - Generates a large number of viable steady state plasmas for advanced high energy tokamaks.
  - Engineering Module
    - Generates a power extraction and conversion system for each plasma. This includes:
      - 3-D power core.
      - Power flow model from fusion to net electric power.
  - Costing Module
    - Estimates the costs of all the power core elements.
    - Includes all the costs associated with plant development, operation and maintenance.
    - Cost of electricity is the final and most important output.

ARIES Systems Code Algorithm – Systems Analysis Toolbox

- A general-purpose custom built systems analysis toolbox is a foundation of the systems code algorithm.
- This toolbox consists of ready to use generic C++ data classes (objects) that serve as building blocks for the systems code modules.
  - Class DesignPoint **holds design-specific data that describe the tokamak machine. Such data are plasma parameters, radial and divertor builds, power flow, etc.**
  - Class Part **holds part-specific data, which describe the elements of the power core, such as blanket for example. These data include contour, areas, volumes, materials, etc.**
  - Class CostingAccount **holds the costing account structure for the machine design.**

Flow Chart

- Input defines the desirable limits for the scan of parametric space.
- Physics, engineering and costing modules are executed in a sequence. (Physics module can be run as a stand alone application).
- Central object of the algorithm consists of the data structures of the **virtual tokamak machine** which exchange data with all the modules and delivers the final result.



ARIES Systems Code Algorithm – Parallel Processing Mode

- An MPI (Message Passing Interface) was utilized in order to take advantage of a multy-processor hardware.
- How it is implemented:
  - Step 1: Initialize the MPI.
  - Step 2: Get the current process ID for each processor and the number of processors.
  - Step 3: Load each processor with a different operating point.
    - This creates a copy of the systems code executable on each processor and runs the operating points that were previously associated with that particular process ID.
  - Step 4: Gather the output on the local machine.
- This splits the operating points between the different processors of the same server and significantly shortens the CPU time.

Plasma Physics Algorithm – Model of Plasma

- A 0-D analysis is performed in order to solve the global plasma power balance and particle balance.
  - Series of models and established physics relationships are used, typically for a fixed plasma geometry.
  - Pedestal profile prescriptions for plasma density and temperature are used. These profiles are validated by the 1.5-D analysis.
  - Plasma power and particle balance are solved by a special set of conservation equations coupled with known physics relations between some of the variables (more details will be given in the paper).
  - Some of the information such as global energy confinement time is obtained by scaling from the present tokamak experiments.
  - Up to 4 heating and current drive systems can be specified based on the analysis outside of the systems code.

Plasma Physics Algorithm
- Input Parameters

Toroidal magnetic field at plasma major radius	B_T	Plasma aspect ratio	A	Normalized toroidal beta	β_n	Cylindrical safety factor	q_{cyl} if +, q_{95} if -.
Plasma triangularity	δ	Exponent on density profile	a_n	Exponent on temperature profile	a_t	Greenwald density fraction	f_{Gw}
Fusion gain	Q	Plasma elongation	κ	Input flattop time	t_{flati}	V-s available	d_{fcs}
Confinement time ratio $t_{global\ particle} / t_{energy}$	t_{pote}	Internal self inductance	a_{li}	Ejima coefficient, used to calculate flux consumption	c_e	V-s required in breakdown phase of discharge	$f_{breakdown}$
Current drive efficiency for source i, i=1,2,3,4	η^i_{CD}	Input current drive power for source i, i=1,2,3,4	P^i_{CD}	Radial location of current drive for source i, i=1,2,3,4	r^i_{CD}	Plasma major radius	R
Starting and final value of confinement multiplier used in search for power balance	h_{min}, h_{max}	Additional value of plasma elongation to use in transport equation	a_{kx}	Charge of impurity i, i=1,2,3	z^i_{imp}	Fraction of electron density of impurity i, i=1,2,3	f^i_{imp}
Ratio of plasma edge temperature to central temperature	t_{rat}	Ratio of plasma edge density to central density	d_{rat}				

- Any of the parameters can be scanned over a desired range in order to produce a physics operating space.

Plasma Physics Algorithm
- Obtaining the Physics Operating Space

Procedure

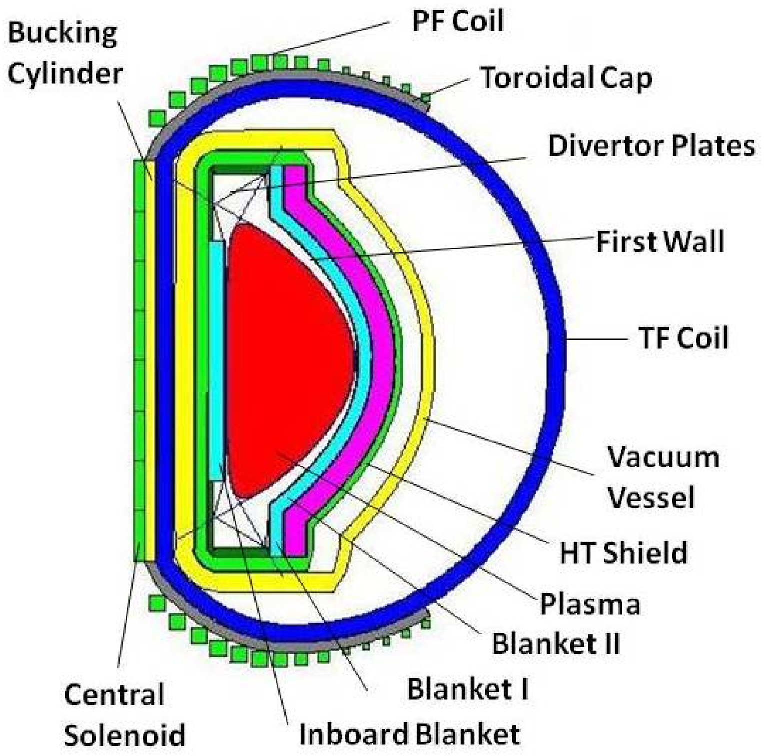
1. Read the input parameters and scan the selected group at any desired range.
2. Perform the physics calculations of the 0-D model.
3. Apply the physics filters to eliminate any unphysical solution.
4. Supply the outputs to the data structure of the virtual tokamak to be further used by the engineering modules.

Example Scan

Parameter	Range
B_T [T]	5-10
β_n	0.03 - 0.06
q_{95}	3.2 - 4.0
n/n_{Gr}	0.4 - 1.0
Q	25 - 50
τ_{He*}/τ_E	5 - 10
R [m]	4.8 – 7.8

Geometry

- ARIES systems code generates a high fidelity 3-D power core model. The example shown is based on the ARIES-AT.
- Contours of all the power core objects are represented by the sequence of 2^{nd} order polynomials, which can be integrated in order to obtain volumes and surface areas as needed.
- The resolution of the contours is adjustable.
- Material composition of the power core elements is represented by
  - Volume and density fractions;
  - Densities;
  - Costs per unit mass and base years for the costs.



Engineering Algorithms

- Definition of Power core Elements
  - Basic Algorithms
    - Thickness and material composition are estimated externally (neutronics) and provided as input.
    - Geometrical contours and cost of electricity are estimated by the code.
      - First Wall
      - HT Shield, thickness estimated based on neutronics.
      - Divertor
      - Blankets
      - Cryogenic Dome
  - Detailed Algorithms
    - Thickness, material composition, geometrical contours and costing are estimated by the code.
      - TF Coil, including toroidal caps and bucking cylinder.
      - PF Coil
- Definition of Power Flow
  - Conversion from fusion to net electric power is estimated by taking into account the actual power core geometry and a detailed model of power transfer from plasma to first wall, blanket and divertor groups.

TF Coil Algorithm – Overall Calculation Procedure

- Steps
  1. Estimate the composition of the coils in terms of volume fractions of different components.
  2. Estimate the total thickness of the coil.
  3. Estimate the geometry of the contours.
  4. Integrate over the volume in order to calculate the total cost.
  5. Provide the total cost as an input to costing algorithms.

TF Coil Algorithm
- Material Composition

- Steps:
  1. Estimate the peak magnetic field in the TF coil.
  2. Calculate the current density in the winding pack.
     1. Superconductor: current density is interpolated from the empirical curves for the material, based on the peak magnetic field.
     2. Copper: current density is given by a formula based on quenching protection.
     3. Effective current density for the winding pack is based on the current densities of the superconductor, copper, as well as the volumetric fractions of the He coolant and protective sheath.
  3. Based on the obtained current densities and a prescribed total current of 40 kA, estimate the cross sectional areas of the winding pack components. Two types of magnets with different components have been modeled:
     1. HTS Composition: YBCO, Cu, Inconel (sheath), He (coolant), Polyamide (insulation).
     2. Nb3Sn Composition: Nb3Sn, Cu, Inconel, He, Polyamide
  4. Estimate the thickness and the cross sectional area of the supporting structure by scaling from structural (finite element) analysis of ARIES-AT. More details on the next slide.
  5. Calculate the total cross sectional are and the area fractions of different components, which for TF coil are identical to volume fractions.

TF Coil Algorithm – Supporting Structure

- TF Coil Casing
  - TF coil thickness was scaled from the value obtained by finite element analysis of the TF coil structure used in ARIES-AT. This includes both winding pack and casing.
  - A scaling formula for thickness was established based on simple beam theory and a multiplier that matches the ARIES-AT coil thickness.

$$a = 0.208 \cdot \sqrt{\frac{3}{16\sigma_b \mu_0} \cdot \frac{B_0 R_0}{R_2 - R_1} \cdot \sqrt{\left(R_2^2 - R_1^2\right)\left(1 + \ln\left(\frac{R_2}{R_1}\right)\right) + R_1 R_2 \left(2 - \ln^2\left(\frac{R_2}{R_1}\right)\right)}}$$

- Bucking Cylinder
  - Located on the inner-most side of the TF coil.
  - Thickness is determined by the hoop stress.
- Toroidal caps are placed on the top and bottom of the TF coil for additional anti-torque support. Their thickness is the same as the one used for bucking cylinder.

TF Coil Algorithm
- Geometry

- A shape based on 2 semi ellipses was adopted based on Leslie Bromberg's suggestion. The length of the straight line portion is proportional to the height of the X-point. Equation of the outer ellipse:

$$\frac{(x - R_0)^2}{a_2^2} + \frac{y^2}{b^2} = 1$$

$$a_2 = b = 0.7(R_2 - R_1)$$

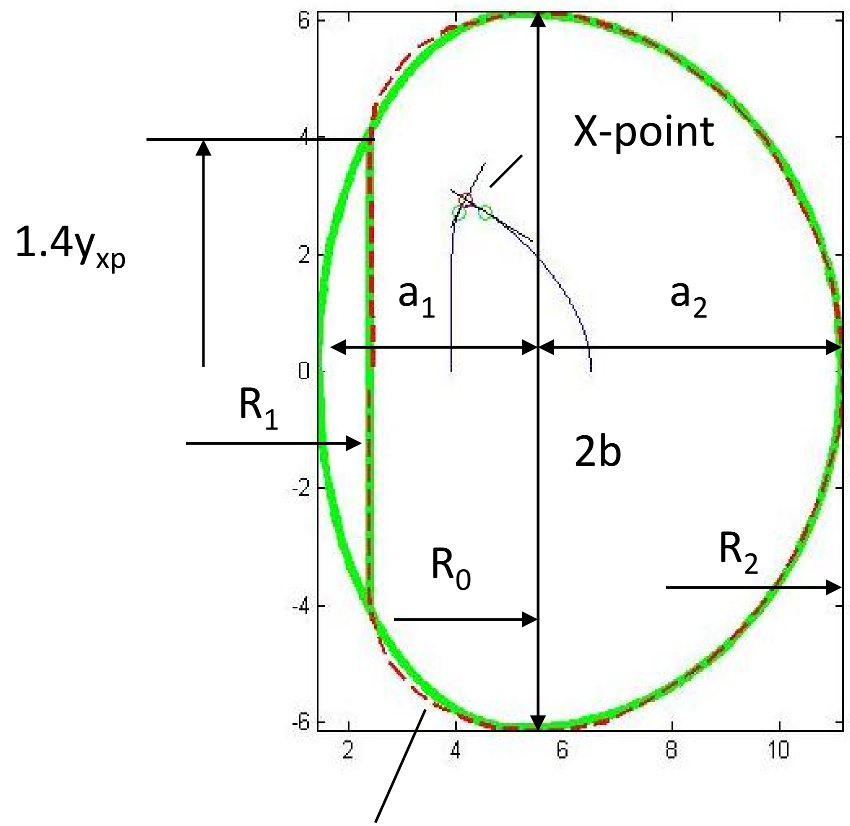
- Equation of the inner ellipse:

$$\frac{(x - R_0)^2}{a_1^2} + \frac{y^2}{b^2} = 1$$

$$a_1 = \frac{R_1 - R_0}{\sqrt{1 - \frac{y_{xp}^2}{b^2}}}$$

- Equation of the straight line:

$$x = R_1$$

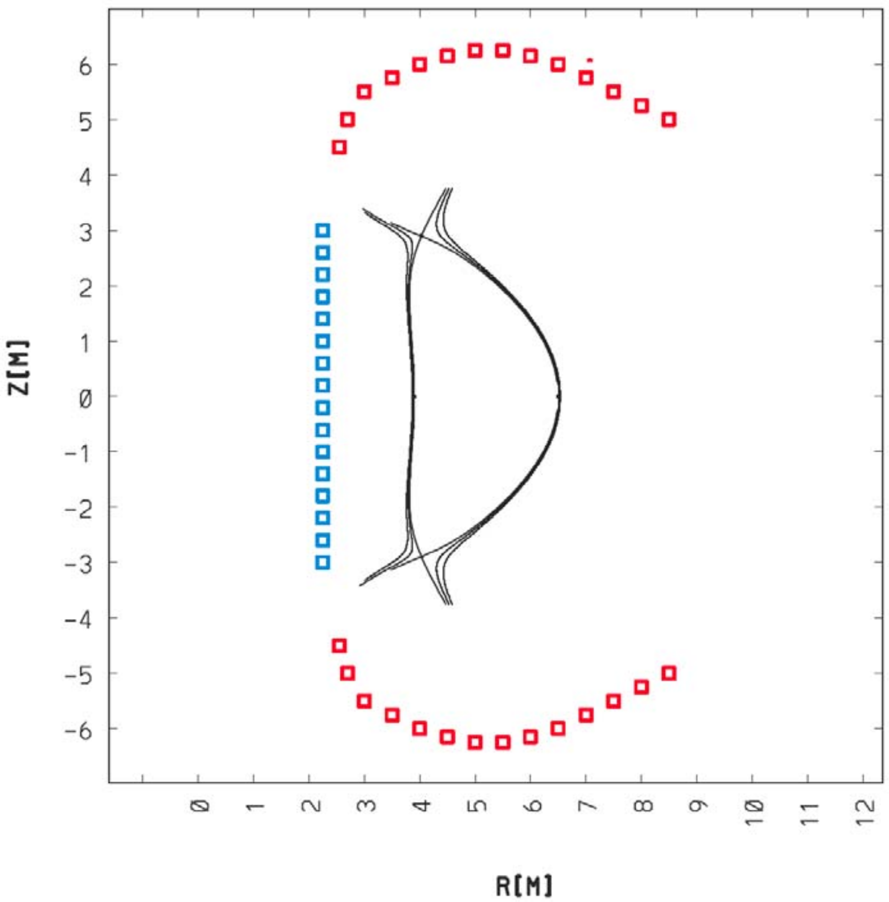


ARIES-AT (dashed line)

PF Coil Algorithm

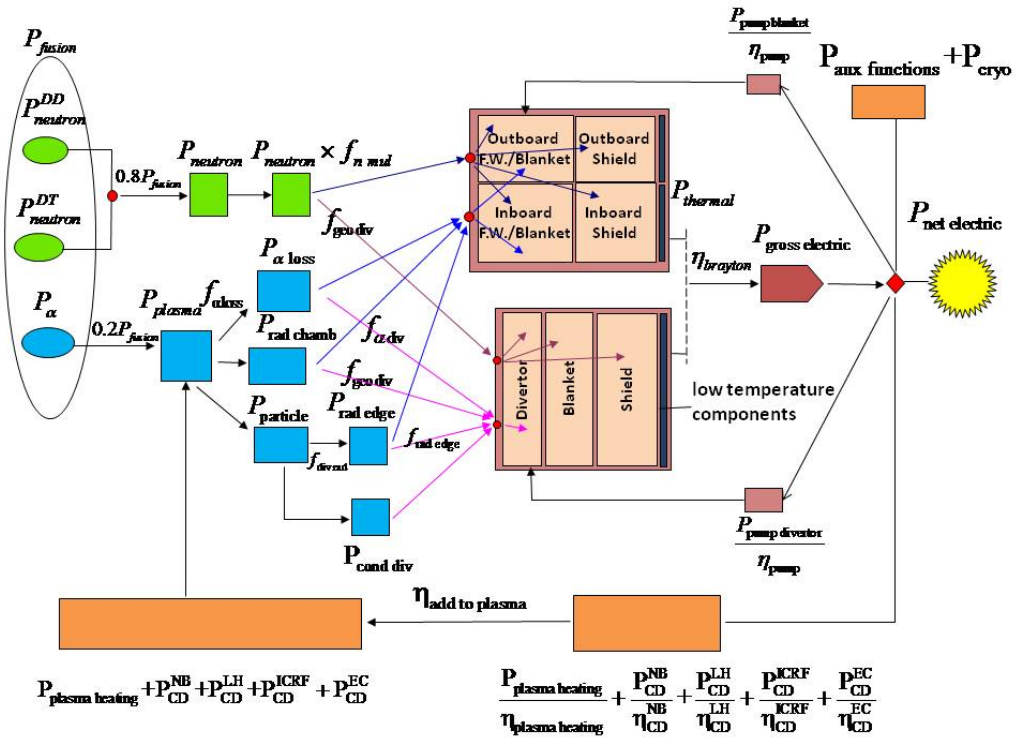
- Steps:

1. Estimate the coil currents at zero flux state. In the current approximation they are assumed to be known and taken as an input.
2. Scale the currents from their values at zero flux state to the values at the given q95 and plasma current.
3. Determine the material compositions and cross sectional areas by using a procedure similar to the one for TF coil.
4. Estimate the amount of structural material needed is based on the hoop stress limit.
5. Place the coils uniformly on the outer surface of the bucking cylinder and toroidal caps.
6. Integrate the cost across the volumes of each individual coil.



Power Flow – Overall Scheme

- Power core is separated into 2 functional groups:
  1. First wall, blankets and HT shield;
  2. Divertor, blanket, shield.
- For the accuracy of calculating the max. heat flux to the first wall, group 1. is split into inboard and outboard section.
- All the fusion power is transformed into thermal power of liquid Pb-17 Li coolant / tritium breeder and conveyed to the high efficiency, closed cycle helium gas turbine.
- Power output from Brayton cycle (gross electric power) supplies the coolant pumps, current drives and various auxiliary functions.
- The remaining, net electric power is the output to the grid.



Costing Accounts

- In the ARIES systems code, costing is handled in following stages:
  - Estimate the cost of each power core element by integration across the volume;
  - Evaluate the sequence of the costing accounts for the power plant;
  - Calculate the cost of electricity.
- Costing accounts are currently being revised in order to reflect a more functional cost structure. The top level accounts are tabulated below.

Direct Costs	**Indirect Costs**
20. Land and Land Rights 21. Structures and Site Facilities 22. Power Core Plant Equipment 23. Turbine Plant Equipment 24. Electric Plant Equipment 25. Heat Rejection Equipment 26. Misc. Plant Equipment 27. Special Materials **90. Total Direct Cost**	91. Construction Services and Equipment 92. Home Office Engineering and Services 93. Field Office Engineering and Services 94. Owner's Cost 95. Process Contingency 96. Project Contingency 97. Interest During Construction **99. Total Cost**

Overview of Data Available

- Databases
  - ARIES Advanced Tokamak with SiC Blanket – $ARIES_{Db}AT(SiC)$
    - Power core configuration and costing accounts are based on ARIES-AT.
    - Magnets, power flow and costing accounts are revised from the ARIES-AT.
    - Wide scans of key design parameters are performed in order to provide a variety of viable data points with net electric power output of 1 GW.
  - ARIES Advanced Tokamak with DCLL Blanket – $ARIES_{Db}AT(DCLL)$
    - The database $ARIES_{Db}AT(SiC)$ is modified by changing from the SiC blanket to the DCLL blanket. This affects:
      - Power core, by insertion of the new blanket.
      - Power flow, by changing to different efficiency of the power cycle and pump.
      - Costing accounts by changing the blanket lifetime and LSA factor from 1 to 2.

Test Cases Studied Up to Date

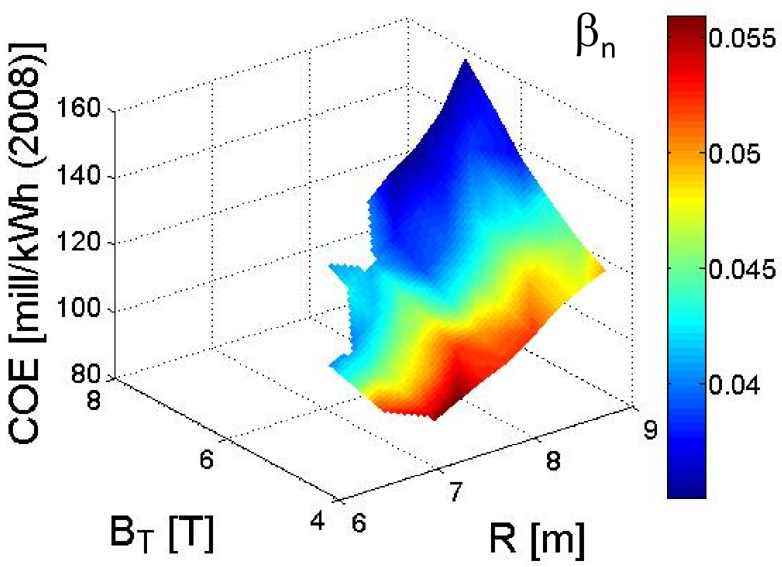
- Test Cases
  - Effect of selected design parameters on cost of electricity:
    - Plasma major radius **R**, toroidal field at plasma major radius **B**, normalized Beta (β_n) – 4 parameter plots generated.
    - Volume-averaged plasma temperature **T** and volume averaged plasma density ρ – 3 parameter plots.
  - Effect of constraints on the COE:
    - Maximum allowed heat flux to divertor is the most significant constraint. Cases studied:
      - Pushing the limit from 8 to 20 MW/m^2 (not realistic).
      - Reducing the heat flux to divertor by increasing the plasma edge radiation fraction to divertor from 75% to 85%.
      - Reducing the heat flux to divertor by increasing the plasma core radiation fraction – in progress.
  - Effect of the blanket model (SiC versus DCLL)

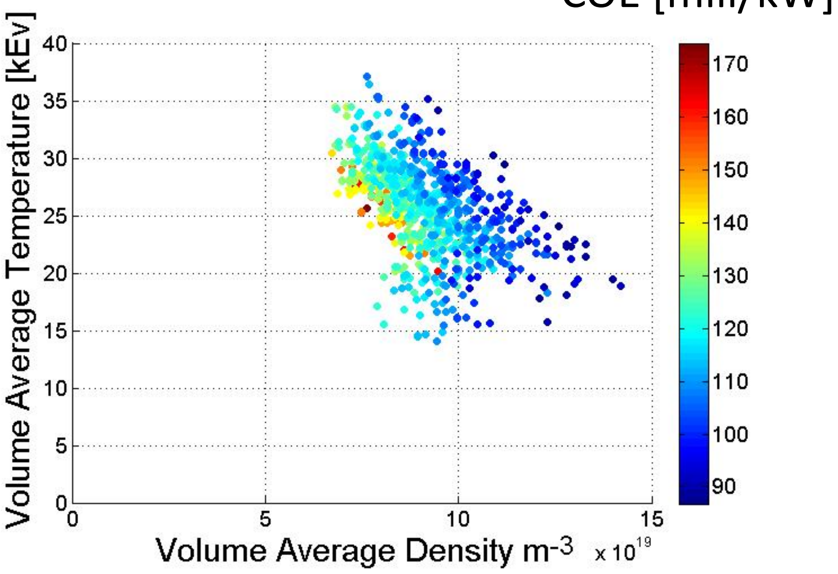
Parameter Scans

- Several millions of tokamak designs with viable plasma operating points were generated by wide parameter scans. The parameters and their scanned intervals are shown in the table below.
- Design points were filtered in order to satisfy the necessary engineering criteria, such as
  - Peak magnetic field in the TF coil < 18 T;
  - Peak flux on divertor < specified limit;
  - Departure of net electric power from 1 GW < 0.1%.

Parameter	**Scanned Interval**
Plasma major radius **R** [m]	4.5 – 9.0
Toroidal field at plasma major radius $\mathbf{B_T}$ [T]	5.0 – 10.0
Normalized plasma pressure β**n** [%]	3.0 – 6.0
Greenwald density fraction [-]	0.4 – 1.1
Cylindrical safety factor $\mathbf{q_{cyl}}$	3.2-4.6
Plasma triangularity δ [–]	0.6 – 0.8
Q	20 – 40
Plasma elongation κ [-]	1.8 – 2.2
Impurity fraction [-]	0.001 – 0.003

COE Versus Selected Design Parameters





COE Versus R, B_T and β_n

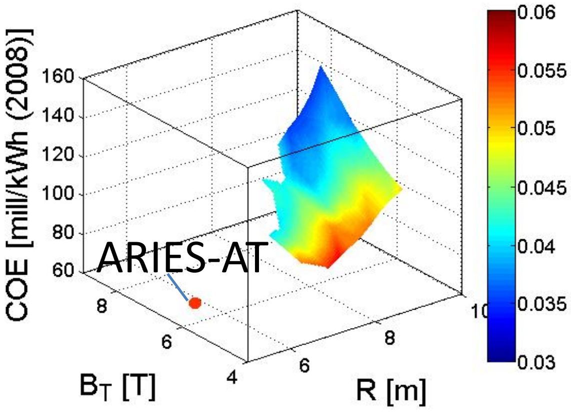
- A 3-D, 4-parameter plot is used to show the locally minimized COE as a function of R, B_T and $\beta_{n.}$
  - COE strongly depends on all 3 parameters.
  - There is a tradeoff between B_T and β_n.

COE Versus Volume Averaged ρ and T

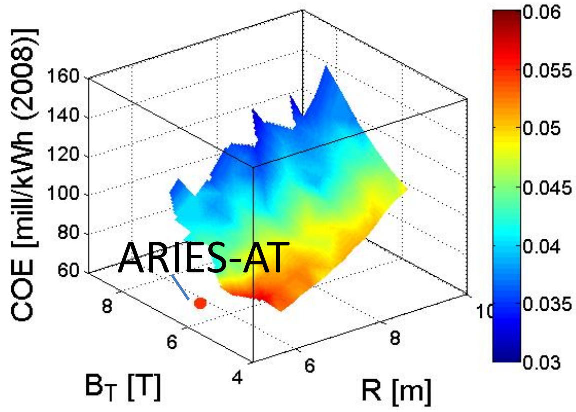
- This plot shows the plasma operating space in volume averaged density and temperature.
- Cost of electricity strongly depends on the volume-averaged density.

Impact of Maximum Allowed Heat Flux to Divertor, Example of COE Vs. R, B_T and β_n (color coded)

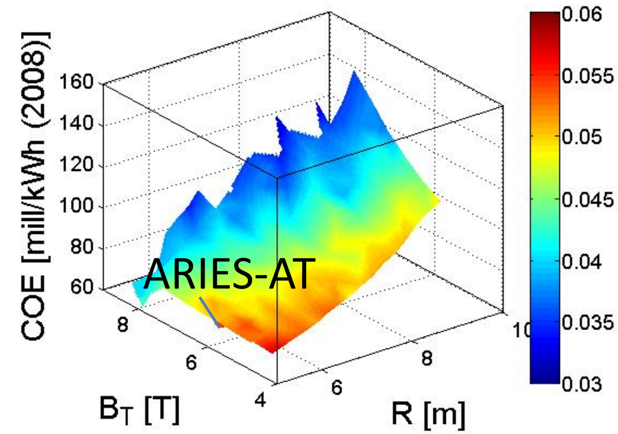
$Q_{div,\ max}$ = 8 MW/m^2



$Q_{div,\ max}$ = 12 MW/m^2



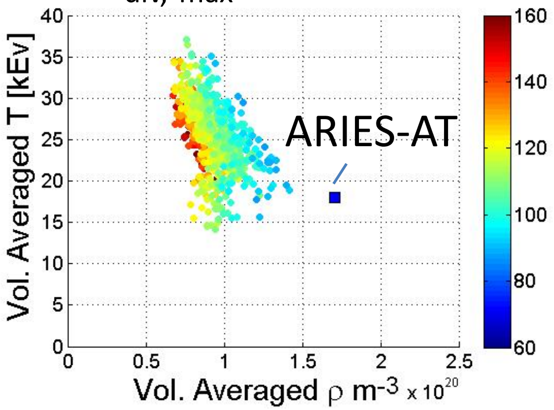
$Q_{div,\ max}$ = 20 MW/m^2



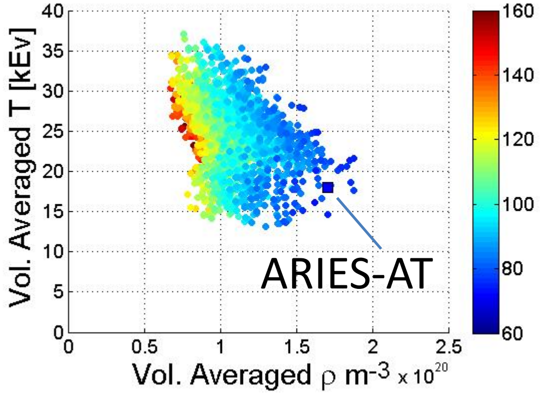
- As the allowed limit to heat flux on divertor increases, more operating points with small plasma major radii become available, therefore we see the smaller COEs.
- The same limit does not seem to affect the range of $B_{T\ or}\ \beta_n$.
- For comparison, ARIES-AT parameters are represented by the single data point (also color coded in βn). These parameters were taken from the published study.
- When the allowed heat flux limit is sufficiently large to allow for operating points at low radii, the optimal COE surface is very close to the ARIES-AT design point.

Impact of Maximum Allowed Heat Flux to Divertor, Example of COE (color coded) Vs. Vol. Averaged Density and Temperature

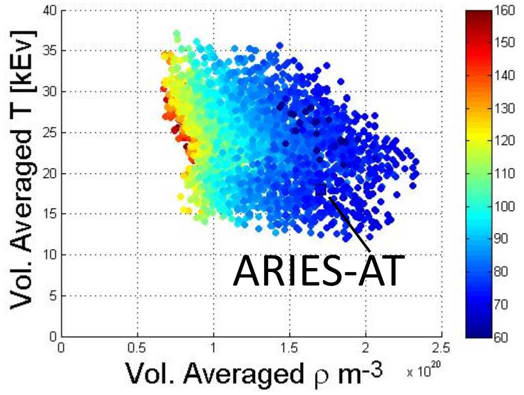
$Q_{div,\ max}$ = 8 MW/m^2



$Q_{div,\ max}$ = 12 MW/m^2



$Q_{div,\ max}$ = 20 MW/m^2

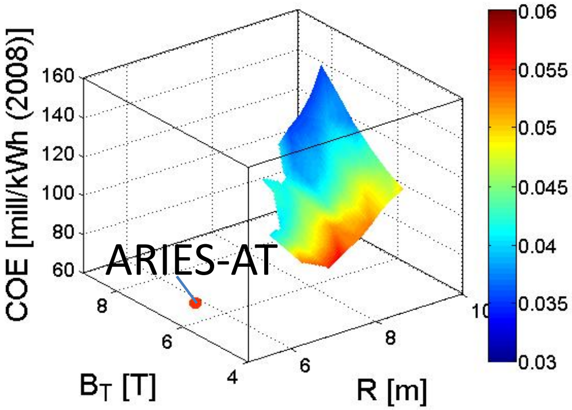


- As the allowed heat flux to divertor increases, more data points with high volume averaged ion density become viable (indicating small machines with low COE).
- Density and temperature of the ARIES-AT fit well with the rest of the data.

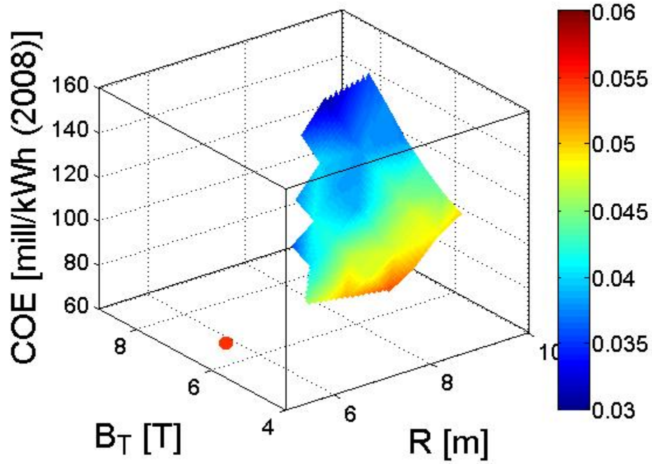
Impact of Plasma Edge Radiation Fraction $f_{div\ rad}$

Reference Case

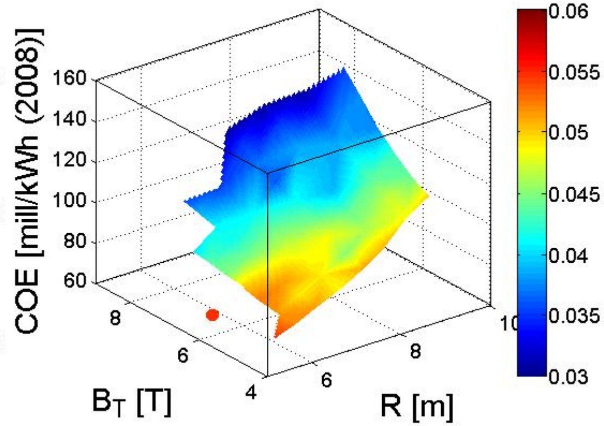
$Q_{div,\ max}$ = 8 MW/m^2
$f_{div\ rad}$ = 75%



$Q_{div,\ max}$ = 5 MW/m^2
$f_{div\ rad}$ = 85%



$Q_{div,\ max}$ = 8 MW/m^2
$f_{div\ rad}$ = 85%



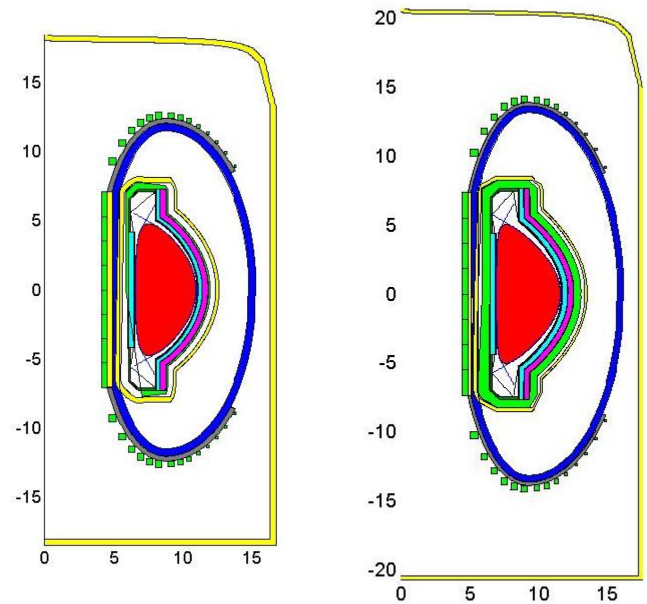
- Plasma edge radiation fraction was increased from 75% (default for all the data generated so far) to 85% in order to reduce the peak heat flux to divertor.
  - Plot on the left is the reference case.
  - Plot in the middle shows that increase in $f_{div\ rad}$ by 10% allows for a reduction in divertor heat flux limit to 5 MW/m^2 without a loss of viable data points.
  - Plot on the right shows that alternatively, the heat flux limit can be kept at 8 MW/m^2 in order to achieve a lower COE and get closer to ARIES-AT.

SiC Versus DCLL Blanket, Same Input Parameters

Comparison of Selected Parameters

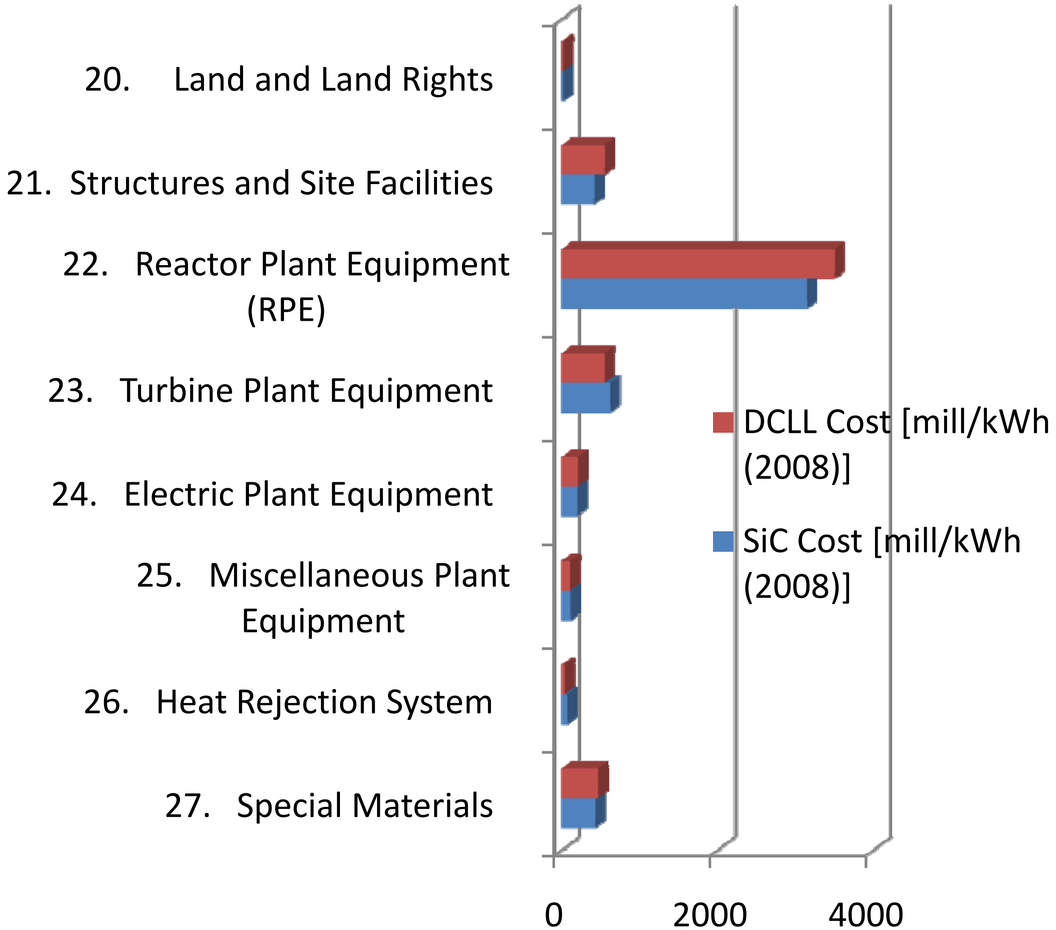
Parameter	SiC Value	DCLL Value
Plasma major radius [m]	9.25	9.25
Toroidal field at plasma major radius [T]	5.0	5.0
Normalized Beta [%]	6.0	6.0
Plasma current [MA]	19.8	19.8
Average Neutron Wall Load [MW/m^2]	1.66	1.66
Fusion Power [GW]	3.7	3.7
Total Auxiliary Power to Plasma [MW]	185	185
Thermal Power [GW]	4.19	4.5
Re-circulated Power [GW]	0.48	1.01
Net Electric Power [GW]	1.93	0.951
Cost of Electricity [mill/kWh]	71.1	150

Comparison of Geometry



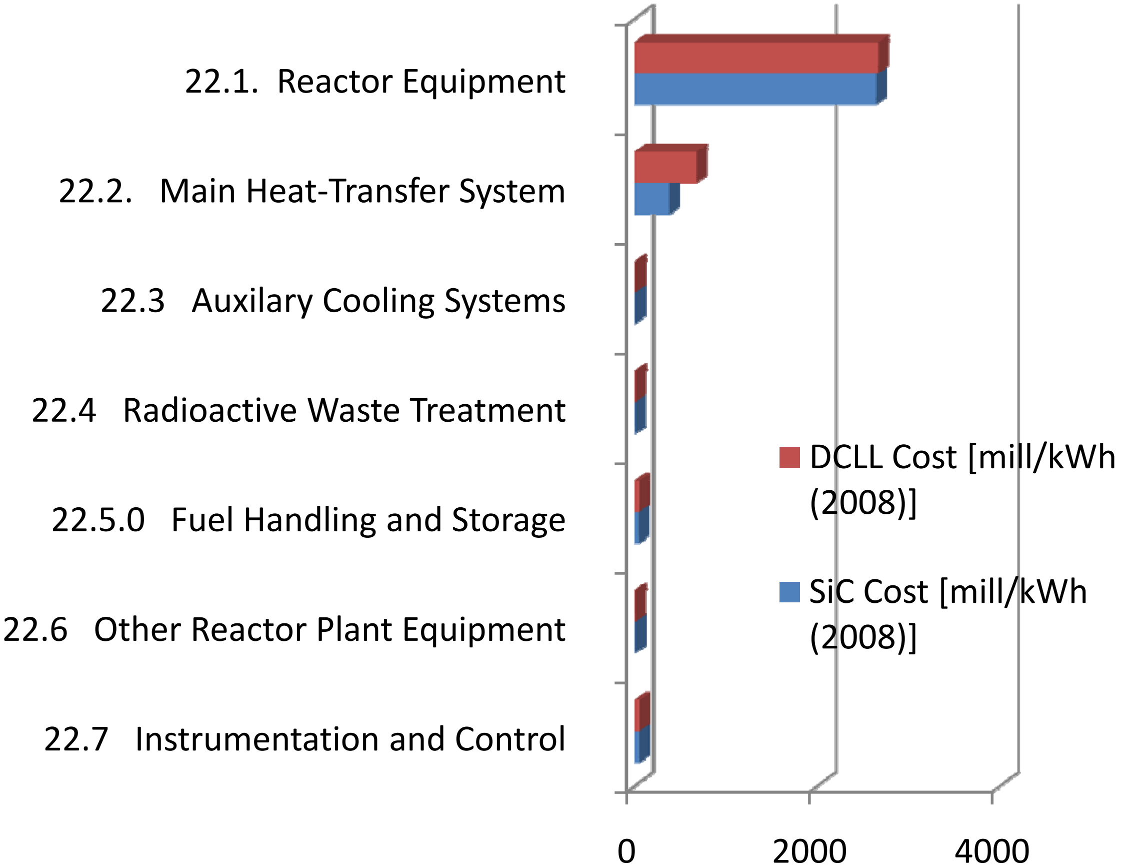
SiC Versus DCLL Blanket – Costing Accounts 20 - 27

- Direct costs for the two blankets are comparable to each other.
- Reactor plant equipment account (22) will be examined separately as the most significant contribution to the total direct cost.

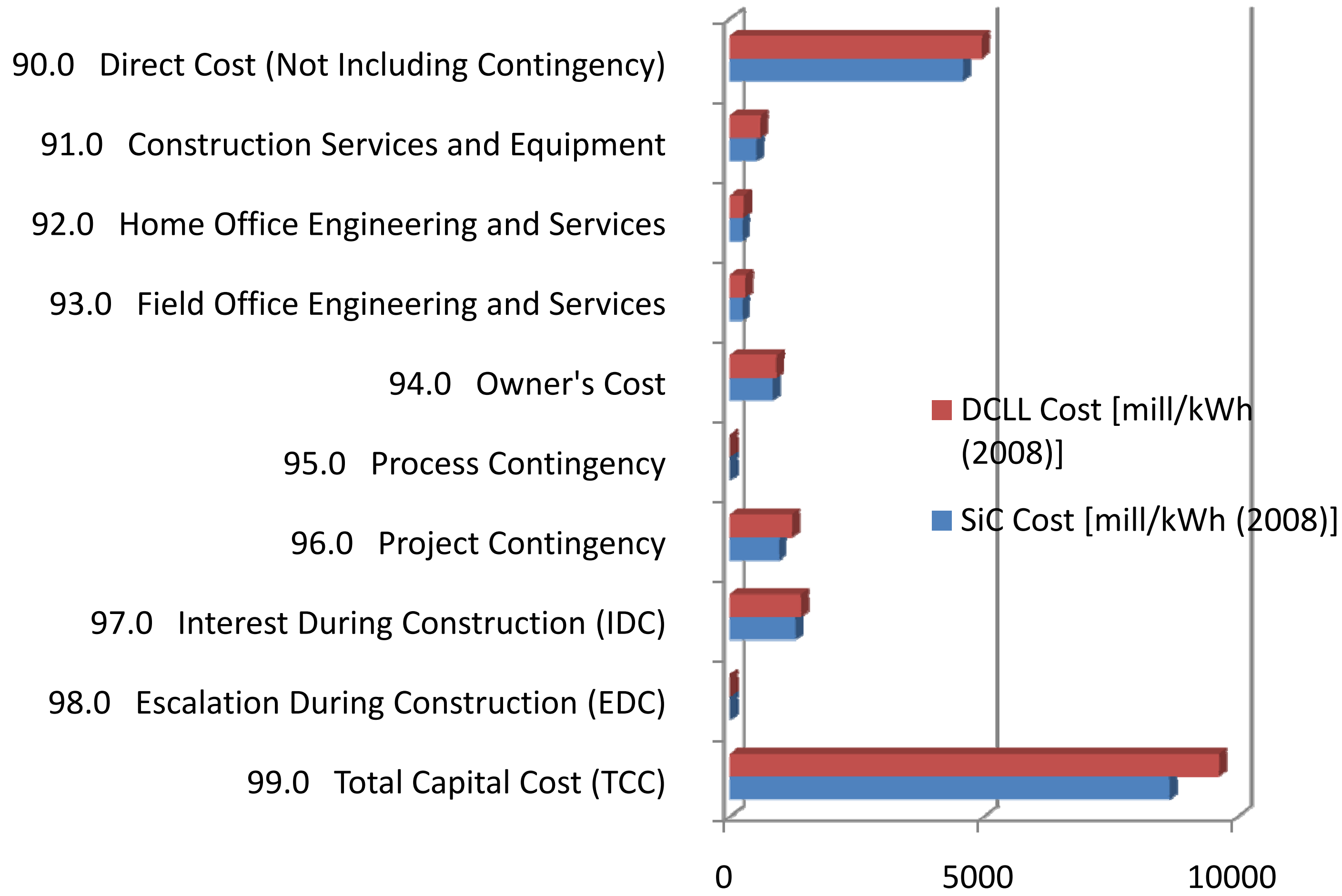


SiC Versus DCLL Blanket - Sub-Accounts of Reactor Plant Equipment (22)

- The only accounts that significantly impact the total cost are the Reactor Equipment (22.1) and the Main Heat Transfer System (22.2).
- The reactor equipment costs of the two machines are almost the same, which makes sense since the power cores are comparable in size and configuration.
- The main heat transfer system costs depend on the thermal power, which is higher for the DCLL blanket.



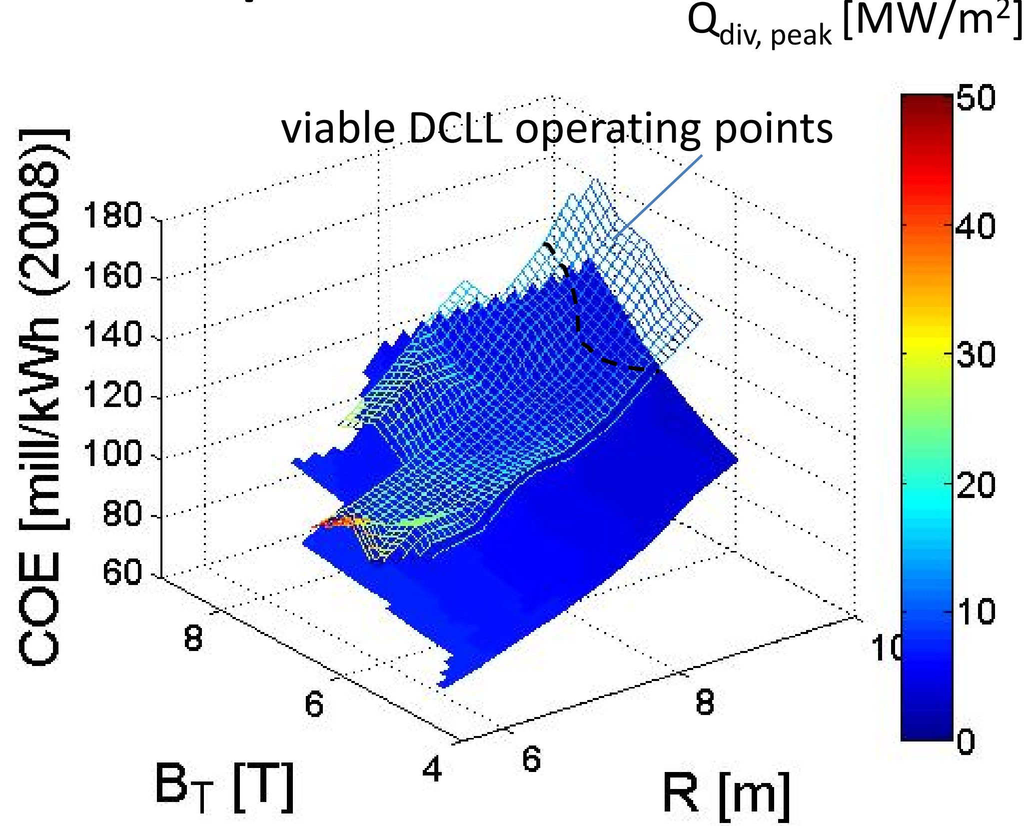
SiC Versus DCLL Blanket – Costing Accounts 90 - 99



- Direct costs differ between the two blankets by 7.5%, while total capital costs differ by 10%. Both differences may be attributed to different LSA factors (1 for SiC, 2 for DCLL).
- Comparison of costing accounts indicate that changing from SiC blanket to DCLL blanket does not impact the total cost of the machine. However, it does impact the power flow by imposing a higher demand for pumping power. This increases the COE.

SiC Versus DCLL Blanket – Comparison Between Machines with 1 GW Electric Power Output

- Optimal COE for the case with SiC blanket is shown as a solid surface, while its counterpart for the DCLL blanket is shown as a mesh.
- Peak heat flux to divertor is color coded, as shown on the side bar.
- Plasma edge radiation fraction is set to 85%.
- Observations:
  - Optimal operating points with SiC blanket cover the entire range of R and B_T without exceeding the flux to divertor of 8 MW/m^2.
  - Their DCLL counterparts have a higher COE and a stronger variation in the heat flux to divertor on the same range of R, B_T.
  - Viable DCLL operating points are only those located above the dashed line



Overall Minima:

-SiC case: 69.9 mill/kWh

-- DCLL case: 143 mill/kWh

Summary of Results Shown

- Recently generated database(s) of viable tokamaks provide a large number of data points, which confirm a strong dependence of COE on several significant parameters, such as plasma major radius, toroidal field at plasma major radius, normalized beta, and volume averaged plasma ion density.
- In case where SiC blanket was used:
  - ARIES-AT data point is very close to the optimal COE surface. The volume averaged density and temperature fall into the optimal region predicted by the database.
  - Limit to heat flux on divertor emerges as a strong constraint, which can be alleviated by increasing the radiation fraction from the plasma edge. By increasing the fraction of impurities, core radiation fraction can be also increased, which might allow for further reduction in the machine size and cost.
- DCLL blanket versus SiC blanket:
  - The question is what cases are the most relevant for comparison. When the identical input data were used to generate two machines with two different blankets, it became apparent that the power flows were not compatible, which resulted in different net electric powers by a factor of 2. The geometry and cost of the hardware are not very far apart, DCLL being slightly more expensive.
  - When the equivalent machines are compared (1 GW net electric power, optimized for COE) , the COE of those with the DCLL blanket was consistently higher by about 40 mills/kWh. This is probably due to the fact that these machines need to retrieve more thermal power from the plasma (need higher fusion power, larger blankets, larger radii) in order to yield the same net electric power as the machines with the SiC blanket.