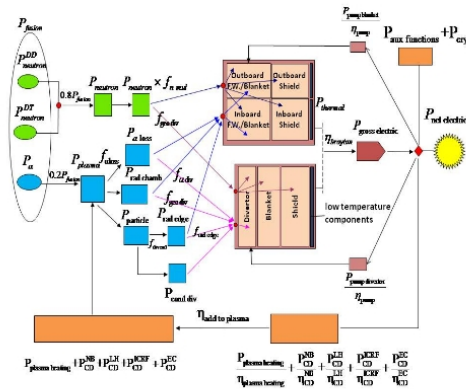
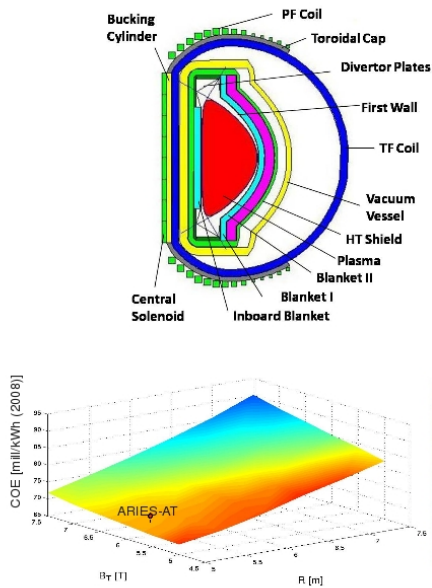
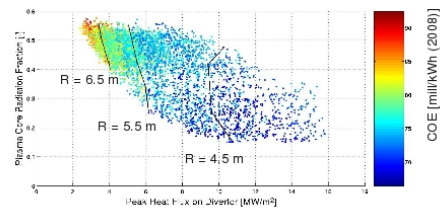


ARIES Systems Code User's Guide

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$$COE = \frac{C_{AC} + (C_{O\&M} + C_{SCR} + C_F) \cdot (1+y)^Y}{8760 \cdot P_E \cdot p_f} + C_{D\&D}$$



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1 Getting Started

Directory Tree

1. "**Archive**" - contains the complete archived code, which can be used as a restoration point for corrupted files, etc.
2. "**PlasmaPhysics**" - contains the plasma physics code which generates the viable operating plasmas for given parameters.
3. "**AriesSystemsCode**" - contains the engineering and costing algorithms, which use the output from the plasma physics code as input file and generate the remainder of the power plant model.
4. "**MatlabPlotScripts**" - contains the post-processing code, which consists of the Matlab scripts for plotting and analysis of the parameters of interest.

System Requirements The application works “out of the box” on any brand of Linux operating system with the standard GNU compiler package. The compilers required are g++ and gfortran. For other operating systems or compiler programs, some modifications to the source code may need to be made.

Installation

1. Make a work directory for the systems code, such as “asc”
> `mkdir asc`
2. Copy the content of the *Archive* directory into the work directory
> `cp Archive/* asc/.`
3. Extract the archive into the work directory:
> `cd asc`
> `tar -xzf PlasmaPhysics.tar.gz`
> `tar -xzf AriesSystemsCode.tar.gz`
> `tar -xzf MatlabPlotScripts.tar.gz`

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Building the Executable Binary The plasma physics module is located in the directory *PlasmaPhysics*. The source code is in the file named “**sysplas_PC.F**”.

The executable is built by using the *make* utility from the command prompt:

```
> cd PlasmaPhysics
> make
```

The instructions to build the executable are written in the file named “**makefile**”, listed in Alg. 2.1.

Setting Up the Input Parameters The input data files are named “**corona**”, “**inpar**” and “**inpar2**”. The input file “**corona**” contains the plasma equilibrium data and remains intact. The files named “**inpar**” and “**inpar2**” contain the plasma parameters which are subject to modification by the user. All the parameters that remain fixed during the run are prescribed in “**inpar**”, while the variable parameters are prescribed in “**inpar2**”.

In order to find the viable plasmas for the power plant model, a set of different parameters needs to be scanned within some chosen intervals. For each parameter, a scan is completely defined by a sequence of 3 variables: the number of sampled values, the initial value and the final value. These variables are prescribed in the file “**inpar2**”, as shown in Alg. 2.2. The user has a choice of fixing some of the parameters that appear in “**inpar2**” to their default values, instead of scanning them. This is done by setting the number of sampled values for those parameters equal to 1 and specifying their default values in the input file named “**inpar**”. The listing of the “**inpar**” is shown in Alg. 2.3. The nomenclature for all the input parameters is given in Table 2.1.

Example As shown in the Alg. 2.2 listing of the “**inpar2**” file, the normalized beta (β_N) is given 3 values by setting $n_{betan} = 3$. The initial value is $betans = 0.04$ and the final value is $betanf = 0.06$. The algorithm assumes equal increments, so the middle value is exactly between $betans$ and $betanf$. In the same listing, the auxiliary power is assigned a single value by setting $npaux = 1$. When this is the case, the initial and final values of the auxiliary power $pauxs$ and $pauxf$ are ignored by the algorithm, even though they may have some numerical values assigned to them. Instead, the algorithm reads the value $paux = 37.00$ from the “**inpar**” file, as shown in Alg. 2.3.

Algorithm 2.1 Listing of “**makefile**”.

```
PlasmaPhysics.exe: sysplas_PC.F
                    gfortran sysplas_PC.F -o PlasmaPhysics.exe
clean:
rm PlasmaPhysics.exe
```

Algorithm 2.2 Listing of “inpar2”.

<pre> &inpar2 nbt⁽¹⁾ = 3 bts⁽¹⁾ = 5.00 btf⁽¹⁾ = 7.0 nbetan⁽²⁾ = 3 betans⁽²⁾ = 0.040 betanf⁽²⁾ = 0.060 nqcyl⁽³⁾ = 2 qcyls⁽³⁾ = -3.200 qcylf⁽³⁾ = -4.600 ndelta⁽⁴⁾ = 2 deltas⁽⁴⁾ = 0.60 deltaf⁽⁴⁾ = 0.80 nan⁽⁵⁾ = 1 ans⁽⁵⁾ = 0.00 anf⁽⁵⁾ = 1.0 nat⁽⁶⁾ = 1 ats⁽⁶⁾ = 1.0 atf⁽⁶⁾ = 2.0 npaux⁽⁷⁾ = 1 pauxs⁽⁷⁾ = 5.00 pauxf⁽⁷⁾ = 40.0 nfracgw⁽⁸⁾ = 3 fracgws⁽⁸⁾ = 0.90 fracgwf⁽⁸⁾ = 1.10 </pre>	<pre> nQ⁽⁹⁾ = 2 Qs⁽⁹⁾ = 20.0 Qf⁽⁹⁾ = 40. nak⁽¹⁰⁾ = 3 aks⁽¹⁰⁾ = 1.80 akf⁽¹⁰⁾ = 2.20 ntpote⁽¹¹⁾ = 1 tpotes⁽¹¹⁾ = 5.0 tpotef⁽¹¹⁾ = 10. nrmaj⁽¹²⁾ = 3 rmajs⁽¹²⁾ = 4.50 rmajf⁽¹²⁾ = 6.50 netacd⁽¹³⁾ = 1 etacds⁽¹³⁾ = 0.45 etacdf⁽¹³⁾ = 0.45 nfimp1⁽¹⁴⁾ = 3 fimp1s⁽¹⁴⁾ = 0.002 fimp1f⁽¹⁴⁾ = 0.004 nfimp2⁽¹⁵⁾ = 1 fimp2s⁽¹⁵⁾ = 0.000 fimp2f⁽¹⁵⁾ = 0.002 nfimp3⁽¹⁶⁾ = 1 fimp3s⁽¹⁶⁾ = 0.000 fimp3f⁽¹⁶⁾ = 0.002 &end </pre>
--	---

Algorithm 2.3 Listing of “inpar”.

<pre> &inpar bt⁽¹⁾ = 6.00 asp⁽¹⁷⁾ = 4.00 betan⁽²⁾ = 0.0450 qcyl⁽³⁾ = -3.500 delta⁽⁴⁾ = 0.600 an⁽⁵⁾ = 0.4720 at⁽⁶⁾ = 0.964 paux⁽⁷⁾ = 37.00 fracgw⁽⁸⁾ = 1.100 Q⁽⁹⁾ = 20.00 ak⁽¹⁰⁾ = 2.00 tflat⁽¹⁸⁾ = 1000. dfcs⁽¹⁹⁾ = 300. tpote⁽¹¹⁾ = 10.000 ali⁽²⁰⁾ = 0.50 ce⁽²¹⁾ = 0.45 brkdwnflux⁽²²⁾ = 10. etacd⁽¹³⁾ = 0.300 powcdi⁽²³⁾ = 0.00 rcd⁽²⁴⁾ = 0.75 etacd1⁽²⁵⁾ = 0.000 powcd1i⁽²⁶⁾ = 0.00 fcd1i⁽²⁷⁾ = 0.00 rcd1⁽²⁸⁾ = 0.00 </pre>	<pre> etacd2⁽²⁹⁾ = 0.000 powcd2i⁽³⁰⁾ = 0.00 fcd2i⁽³¹⁾ = 0.000 rcd2⁽³²⁾ = 0.75 etacd3⁽³³⁾ = 0.000 powcd3i⁽³⁴⁾ = 0.00 fcd3i⁽³⁵⁾ = 0.00 rcd3⁽³⁶⁾ = 0.00 etacd4⁽³⁷⁾ = 0.000 powcd4i⁽³⁸⁾ = 0.00 fcd4i⁽³⁹⁾ = 0.000 rcd4⁽⁴⁰⁾ = 0.00 rmaji⁽¹²⁾ = 6.50 hmin⁽⁴¹⁾ = 0.5 hmax⁽⁴²⁾ = 4.0 akx⁽⁴³⁾ = 1.8000 zimp1⁽⁴⁴⁾ = 18.0 fimp1⁽¹⁴⁾ = .002000 zimp2⁽⁴⁵⁾ = 18.0 fimp2⁽¹⁵⁾ = .0000 zimp3⁽⁴⁶⁾ = 30.0 fimp3⁽¹⁶⁾ = .0000 trat⁽⁴⁷⁾ = 0.000 drat⁽⁴⁸⁾ = 0.27 </pre>
	<pre> &end </pre>

2 Generating Viable Plasmas for System Models of Tokamak Power Plants

Table 2.1: List of input parameters to the plasma physics algorithm.

Index	Parameter	Symbol	Units
1	Toroidal magnetic field at plasma major radius.	B_T	T
2	Normalized beta.	β_N	-
3	Cylindrical safety factor.	q_{cyl}	-
4	Plasma triangularity.	δ	-
5	Exponent on plasma density profile.	a_n	-
6	Exponent on plasma temperature profile.	a_t	-
7	Total power into plasma for power balance.	P_{aux}	MW
8	Greenwald density fraction.	f_{Gw}	-
9	Fusion gain = P_{fusion}/P_{aux}	Q	-
10	Plasma elongation	κ	-
11	Ratio of effective particle confinement time to energy confinement time.	t_{pote}	-
12	Plasma major radius.	R	m
13	Current drive efficiency for generic heating/CD source.	η_{CD}	-
14	Impurity fraction* 1	f_{imp1}	-
15	Impurity fraction 2	f_{imp2}	-
16	Impurity fraction 3	f_{imp3}	-
17	Plasma aspect ratio	s_p	-
18	Flatop time	t_{flat}	s
19	Poloidal flux swing required to raise plasma current	d_{fcs}	?
20	Plasma internal self inductance	ali	?
21	Ejima coefficient	ce	?
22	Breakdown flux	$f_{breakdown}$	?
23	Power from generic CD source	P_{CD}	MW
24	Term in the equation for the generic CD source	r_{CD}	?
25-28	Defining parameters for CD source 1.	$\eta_{CD}^1, P_{CD}^1, f_{CD}^1, r_{CD}^1$	
29-32	Defining parameters for CD source 2	$\eta_{CD}^2, P_{CD}^2, f_{CD}^2, r_{CD}^2$	
33-36	Defining parameters for CD source 3	$\eta_{CD}^3, P_{CD}^3, f_{CD}^3, r_{CD}^3$	
37-40	Defining parameters for CD source 4	$\eta_{CD}^4, P_{CD}^4, f_{CD}^4, r_{CD}^{14}$	
41-42	Minimum and maximum values of the H factor	h_{min}, h_{max}	-
43	?	k_x	
44-46	Charge of impurity for impurities 1, 2 and 3.	$z_{imp1}, z_{imp2}, z_{imp3}$	-
47	Ratio of plasma temperature at center to edge	t_{rat}	-
48	Ratio of plasma density at center to edge	d_{rat}	-

*Fraction of electron density.

Algorithm 2.4 Listing of “runphysics.sh”

```
#!/bin/sh
date;
./PlasmaPhysics.exe;
date;
printf "Plasma Physics Execution Finished\n";
```

Algorithm 2.5 A single line from the output file “**sysout**”, which corresponds to a typical viable plasma operating point. The numerical values correspond to an array of 55 different parameters that describe this plasma.

4.500E+00 ⁽¹²⁾	4.000E+00 ⁽¹⁷⁾	5.000E+00 ⁽¹⁾	5.023E+00 ⁽⁴⁹⁾	4.000E-02 ⁽²⁾	4.600E+00 ⁽⁵⁰⁾
2.968E+00 ⁽³⁾	6.000E-01 ⁽⁴⁾	4.720E-01 ⁽⁵⁾	9.640E-01 ⁽⁶⁾	9.000E-01 ⁽⁸⁾	2.000E+01 ⁽⁹⁾
1.800E+00 ⁽¹⁰⁾	2.455E+00 ⁽⁵¹⁾	7.698E+01 ⁽⁵²⁾	2.813E+00 ⁽⁵³⁾	1.013E+01 ⁽¹¹⁾	1.025E+20 ⁽⁵⁴⁾
1.159E+01 ⁽⁵⁵⁾	0.000E+00 ⁽¹⁸⁾	2.267E+01 ⁽⁵⁶⁾	5.473E-01 ⁽⁵⁷⁾	7.825E+00 ⁽⁵⁸⁾	9.991E-01 ⁽⁵⁹⁾
3.000E-01 ⁽¹³⁾	5.404E-02 ⁽²³⁾	9.954E+00 ⁽⁷⁾	1.958E+00 ⁽⁶⁰⁾	2.828E-04 ⁽⁶¹⁾	4.957E+00 ⁽⁶²⁾
3.066E-01 ⁽⁶³⁾	1.806E+00 ⁽⁶⁴⁾	0.000E+00 ⁽⁴⁷⁾	2.700E-01 ⁽⁴⁸⁾	4.572E-41 ⁽²⁵⁾	1.774E+14 ⁽²⁹⁾
4.572E-41 ⁽³³⁾	1.759E+14 ⁽³⁷⁾	2.000E-03 ⁽¹⁴⁾	0.000E+00 ⁽¹⁵⁾	0.000E+00 ⁽¹⁶⁾	2.031E+01 ⁽⁶⁵⁾
9.158E-04 ⁽⁶⁶⁾	1.000E+00 ⁽⁶⁷⁾	9.712E-02 ⁽⁶⁸⁾	7.698E-01 ⁽⁶⁹⁾	1.078E+02 ⁽⁷⁰⁾	6.097E+01 ⁽¹⁹⁾
0.000E+00 ⁽⁷¹⁾	1.303E+00 ⁽⁷²⁾	1.960E+00 ⁽⁷³⁾	2.374E+00 ⁽⁷⁴⁾	3.572E+00 ⁽⁷⁵⁾	3.982E+01 ⁽⁷⁶⁾
1.691E+00 ⁽⁷⁷⁾					

Running the Code A simple shell script runphysics.sh is provided in order to define the running parameters of for the executable binary. The listing of the shell script is shown in Alg. 2.4.

To submit the program to run as a background process at the local machine, the following command can be issued from the command prompt:

```
> ./runphysics.sh > log.txt &
```

where “**log.txt**” is the log file with code execution information.

Output Data The plasma-defining parameters are written in the output data file named “**sysout**”. The first line of the output file contains an integer which shows the total number of plasma operating points that are computed. Each of the remaining lines consists of an array of parameters that describe a single plasma operating point. Each plasma is described by the total of 55 parameters. A typical array of values in a single line is shown in Alg. 2.5. The indices enclosed in parentheses are used for linking the parameter values with the nomenclature tables. Indices 1-48 correspond to the input parameters described in Table 2.1. Indices 49-77 mark the output parameters that are described in Table 2.3. Each plasma is a viable operating point, i. e. it has been filtered through the physics rejection criteria by the algorithm.

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Table 2.3: Output parameters calculated by the plasma physics module of the ARIES systems code.

Index	Parameter	Symbol	Units
49	Plasma current	I_P	MA
50	MHD safety factor	q_{MHD}	-
51	H98(y,2) multiplier on energy confinement scaling	h_{factor}	-
52	Current diffusion time	τ_j	s
53	Energy confinement time	τ_e	s
54	Volume average electron density	x_{ne}	m ⁻³
55	Volume average temperature	T_{ave}	keV
56	L to H-mode threshold power	$P_{L\ to\ H}$	MW
57	Average neutron wall load at plasma surface	x_{nwall}	MW/m ³
58	Bremsstrahlung radiation loss	P_{brem}	MW
59	Bootstrap current fraction	f_{BS}	-
60	Cyclotron radiation loss	P_{cycl}	MW
61	Ohmic power in plasma	P_{Ohm}	MW
62	Line radiation loss	P_{line}	MW
63	Fast alpha beta	β_f	-
64	Effective charge	z_{eff}	-
65	Peak temperature	T_0	keV
66	External CD fraction of total plasma current	f_{CD}	-
67	Total non-inductive fraction of total plasma current	f_{ni}	-
68	Density fraction of helium (fraction of electron density)	f_{He}	-
69	Density fraction of DT fuel (fraction of electron density)	f_{DT}	-
70	Plasma stored energy	W_{tot}	MJ
71	Loop voltage in plasma	V_{loop}	V
72	Density profile peak-to-volume average	d_{ptav}	-
73	Temperature profile peak-to-volume average	t_{ptav}	-
74	Poloidal beta	β_P	-
75	Toroidal beta	β_T	-
76	Alpha power in plasma	P_α	MW
77	Ratio of loss power to L-H threshold power	p_{loplh}	-

3 Generating System Models of Tokamak Power Plants

Building the Executable Binary The suite of engineering and costing algorithms is located in the directory *AriesSystemsCode*. Similarly to the plasma physics module, the executable is built by executing the command *make* in the command prompt. The makefile is listed in the Alg. 3.1.

By issuing the command

```
> make clean;
```

the user can delete the executable and the object files.

Setting Up the Input Parameters

Plasma-Defining Input Parameters The input parameters that define the plasma are imported from the plasma physics module by the following steps:

1. Edit the output file “**sysout**” located in *PlasmaPhysics* directory.
2. Remove the topmost line that shows the total number of plasmas.
3. Save the file, make a copy named “**sysout.data**” and place it in the *AriesSystemsCode/InputData* directory:

```
> cp sysout ../AriesSystemsCode/InputData/sysout.data
```

Display Mode The ARIES systems code has two different display modes for the output parameters: a debugging mode for a single design point determined by a single line of the “**sysout.data**” file and a production mode for the entire range of different design points. The debugging mode is set up by modifying the line 54 of the file *Aries.cpp* to

```
string dispmode = "system";
```

The production mode is set up by modifying the same line to

```
string dispmode = "coe";
```

The output formats for each of these modes will be described in one of the following sections.

Power Plant-Defining Parameters The engineering and costing parameters that define the tokamak power plant remain constant during the scan of the viable plasmas. These parameters are discussed in Ref. (1) and will be covered in Chapter 4.

Algorithm 3.1 Listing of the “**makefile**” for engineering and costing module of the ARIES systems code.

```
AriesIndy.exe : Aries.o Geometry.o Cost.o CostingAccount.o \
    DesignPoint.o \
    Part.o
g++ -o AriesIndy.exe Aries.o \
    Geometry.o Cost.o CostingAccount.o \
    DesignPoint.o \
    Part.o
Aries.o : Aries.cpp Geometry.cpp Cost.cpp CostingAccount.cpp DesignPoint.cpp \
    Part.cpp
g++ -c Aries.cpp Geometry.cpp Cost.cpp CostingAccount.cpp DesignPoint.cpp \
    Part.cpp
clean : rm AriesIndy.exe Aries.o Geometry.o Cost.o CostingAccount.o DesignPoint.o Part.o
```

Algorithm 3.2 Shell script “runaries.sh”.

```
#!/bin/sh
date;
datpt=0;
while [ $datpt -le 2000000 ]; do
./AriesIndy.exe $datpt; # Execute the aries code
datpt='expr $datpt + 1' # Increment datpt
done
printf "ARIES Code Execution Finished\n";
date;
```

Running the Code The code is recommended to run as a background process, by submitting the command

```
> ./runaries.sh > log.txt &
```

The content of the shell script “**runaries.sh**” is displayed in the Alg. 3.2.

The shell script is set up to execute an arbitrary section of the input file “**sysout.data**” one line at a time, by using a Unix loop. This method has an advantage over reading the entire file into the memory of the computer and then executing it for two reasons:

- Only one line of data is in the memory at a time, which frees lots of the server memory for other users or purposes. This is significant if the “**sysout.data**” contains several millions of lines.
- To save on the computational time, multiple executable binaries can be created and utilized to process different portions of the “**sysout.data**” file at the same time. This is a useful strategy on a multi-processor server.

3 Generating System Models of Tokamak Power Plants

The Unix loop is initialized on line 3 of the shell script by assigning the initial value to the variable *datpt*. In the example shown in Alg. 3.2, the value “0” corresponds to the first line of the “**sysout.data**”. In the same example, the loop is set up to vary the line number *datpt* from 0 to 2000000. Line 5 of the shell script executes the code, while line 6 increments the *datpt* until the termination condition is met. The *date* statements on the lines 2 and nine are inserted in order to provide the information on the total execution time.

Example To execute a single line number 175 of the file “**sysout.data**”, the lines 3 and 4 of the “**runaries.sh**” shell script need to be modified as:

```
datpt = 174;  
while [ $datpt -le 174 ]; do
```

Remember that C++ counts the first line as line 0, therefore 175-1=174.

Output Data

Case 1: Debugging Mode The ARIES systems code is to run in a debugging mode if the system data for a single power plant needs to be analyzed thoroughly. As previously explained, this mode is enabled by setting the value of the *dispmode* variable to “system”. In this case, the program prints a detailed geometry, engineering and costing information in form of data files that are located in the directory *AriesSystemsCode/OutputParts*. File “**System.data**” contains general system information, such as plasma contour defining parameters, radial builds, volumes, etc. File “**CostingAccounts.data**” contains the costing account structure with cost outputs and cost of electricity as the final result. The remaining files contain the coordinates of the contour lines for the power core elements.

Case 2: Production Mode

Bibliography

- [1] Z. DRAGOJLOVIC, A. R. RAFFRAY, F. NAJMABADI, C. KESSEL, L. WAGANER, L. EL-GUEBALY, L. BROMBERG, An advanced computational algorithm for systems analysis of tokamak power plants, Fusion Engineering and Design, 2009.