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Validation and sensitivity of CFETR design using EU systems codes

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The Chinese Fusion Engineering Test Reactor (CFETR) bridges the gap between ITER and a fusion power plant (FPP). The primary objectives of CFETR are: ∼2 GW of fusion power, producing ∼700 MW of net electric power, demonstrate tritium self-sufficiency, operate in steady-state and have a duty cycle of 30-50 %. CFETR is in the pre-conceptual design phase and is currently envisaged to be a four-phase machine (from phase I P_{fus} ∼200 MW to phase IV P_{fus} ∼2 GW). In 2016 the EU and China began a collaboration on topics relating to nuclear fusion research and one topic of the work is on CFETR and DEMO. This contribution documents the progress on the collaboration on systems codes studies of CFETR. Systems codes attempt to model all aspects of a fusion power plant using simplified models (0-D, 1-D) and capture the interactions between plant systems. This allows the user to explore many reactor designs at a high level and optimise for different figures-of-merit (e.g. minimise major radius, R_0, or maximise fusion gain, Q). The EU systems code used for this work is PROCESS, which is the systems code used to create the EU-DEMO baseline designs. This paper details the work on analysing a 2018 CFETR design point in EU systems code PROCESS and the feasibility of the design with regards to meeting the performance objectives and operation of the machine. The work comments on the four-phased nature of the device and the systems code output focuses on phase IV. In combination with systems code, an uncertainty quantification tool is used to investigate the sensitivity of a CFETR design point to changes in the input assumptions in the systems code. This paper details sensitivities of the CFETR design and shows that given the specified inputs and the uncertainties there are a reasonably number of feasible design points around the CFETR phase IV design point that still fulfil the high-level objectives of the machine.

1 Introduction

The purpose of the proposed CFETR is to provide the necessary information to bridge the physics and technology gap between ITER and a FPP. The CFETR design point used for this work has a similar fusion power to DEMO but at a smaller major radius, R_0. The primary objectives of CFETR are: to demonstrate tritium self-sufficiency, to produce significant $P_{e,net}$ from ∼2 GW fusion power, operate in steady-state mode, have a duty cycle of 30-50 % and demonstrate key technologies required for a power plant. The design of CFETR has evolved over the last four years and that progress is documented in [1, 2].

This paper details a 2018 CFETR design point which consists of four operational phases which are detailed in Table 3. The phase IV design point of 7.2 m major radius, ∼ 2.2 GW fusion power and ∼ 740 MW net electric power was used for the systems code work. A description of how the design point was recreated in PROCESS, what assumptions were required and what differences there were is presented. The work then goes on to look at how robust that design point is to uncertainties on a number of key input parameters and if the machine's high-level objectives are still achieved.

2 CFETR in Systems Codes

A systems code aims to model all systems in a fusion power plant (provided a set of user inputs and constraints) to allow the user to explore the parameter space available for machine design. One can optimise inside this parameter space for a given figure-of-merit (e.g. minimise major radius, R_0, or maximise net electric power, $P_{e,net}$). The models included in a systems code are not exhaustive but are at the required accuracy to make the investigation worthwhile. Current EUROfusion DEMO baseline designs are based on output from the fusion reactor systems code PROCESS [3, 4]. PROCESS uses a constrained optimisation routine to find a solution. SYCOMORE is another EU systems code developed by CEA and is used to investigate reactor designs [5]. SYCOMORE uses genetic algorithms to find feasible solutions [6]. The CFETR design work uses the General Atomics (GA) systems code for its design [7]. This work reports on recreating a 7.2 m CFETR design (phase IV) in the systems code PROCESS.

2.1 PROCESS

The recreation of the CFETR design point for this work will focus on the phase IV CFETR design point, as this will be the final outcome of the machine's construction and commissioning path. The phases I-III could be seen as commissioning of CFETR to reach its full operation, as the machine size will remain constant throughout the phases. The ability of the plant systems to handle the different phases will require detailed modelling beyond the scope of systems codes and this work will form part of the CFETR R&D roadmap.

While re-creating the current CFETR design in PROCESS a number of input assumptions were made which are described here. For the PROCESS CFETR run in this paper the bootstrap fraction, f_{bs}, was a fixed input at 75 %. The high bootstrap fraction allows the the machine to operate in steady-state conditions with the other 25 % of the current drive coming from the auxiliary heating and current drive systems. The H-factor is a fixed input and is assumed to be 1.42 as prescribed by the CFETR phase IV design point. While challenging this H-factor is not unachievable and a similar H-factor (1.4) is targeted for ITER. PROCESS uses a radiation corrected H-factor [8] which excludes all core radiation from the loss power. The GA systems code for CFETR only excludes the bremsstrahlung radiation from the loss power in-line with ITER. A more detailed code

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Input	Units	Value	Input	Units	Value
f_{bs}	%	75	R_0	m	7.15-7.25
A	-	3.3	f_{GW}	-	< 1.3
κ	-	2	q_{95}	-	> 3.5
δ	-	0.5	P_{sep}/R_0	MW/m	< 30.7
H_{98y2}	-	1.42	B_T	T	6.45-6.55
η_{NBI}	%	40	Z_{eff}	-	< 2.45
N_{TF}	-	16	P_n	MW/m^2	< 2.3
η_{plant}	%	37.5	B_{max}	T	< 14.3

Table 1: *Table of input assumptions for PROCESS run for recreating the CFETR phase IV design point.*

Parameter	Lower Bound	Upper Bound	CFETR IV
H_{98y2}	1.1	1.42	1.42
B_T [T]	6	7	6.5
R_0 [m]	7.0	7.5	7.2
P_{sep}/R_0 [MW/m]	20	40	30.7

Table 2: *Table of uncertainties used in analysis detailed in §4, the range given and the value for CFETR phase IV.*

	Phase				
Parameter	I	II	III	IV	PROC.
P_{fus} [MW]	120	229	974	2192	2172
P_{recirc} [MW]	199	196	238	265	265
P_{net} [MW]	-107	-58	232	738	733
P_n [MW/m2]	0.12	0.23	0.99	2.23	2.3
β_N [mT/MA]	1	1.2	2	3	2.83
f_{bs}	0.4	0.4	0.5	0.75	0.75
H_{98y2}	1.12	1.25	1.41	1.42	1.42
P_{inj} [MW]	77	75	82	78	55
I_p [MA]	8.61	10.34	13.78	13.78	17.5
B_T [T]	6.5	6.5	6.5	6.5	6.55
$T_e(0)$ [keV]	18	24	36	32	32
$n_e(0)$ [10^{20}m^{-3}]	0.48	0.52	0.78	1.31	1.0
f_{GW}	0.57	0.51	0.57	0.96	0.85
Z_{eff}	2.45	2.45	2.45	2.45	2.45
$\frac{P_{sep}}{R_0}$ [MW/m]	8.52	9.42	15.69	30.7	28
q_{95}	8.87	7.39	5.54	5.54	3.5

Table 3: *CFETR conceptual design plant parameters for four proposed phases of operation and the last column is the PROCESS run.*

Description	Thickness [m]	Total [m]
Machine bore	1.150	1.150
CS thickness	1.100	2.250
Gap: CS - TF	0.155	2.405
Inboard TF coil	1.075	3.480
Gap: TF - TS	0.050	3.530
Thermal shield (TS)	0.040	3.570
Gap: TS and VV	0.050	3.620
Vacuum vessel (VV)	0.150	3.770
Inboard shield	0.150	3.920
Gap: shield/VV - blanket	0.000	3.920
Inboard blanket	1.000	4.920
Inboard scrape-off layer	0.080	5.000
Plasma minor radius	2.200	7.200

Table 4: *CFETR conceptual design radial build, up to R_0 with thicknesses and cumulative thickness.*

than PROCESS is required to fully validate the plasma scenario in CFETR and so a number of physics parameters are input as fixed values for the purposes of this work. For this run the figure-of-merit was to maximise the net electric power.

The divertor protection parameter (P_{sep}/R_0), which is commonly used in fusion power plant design [9] limit was input as 30.7 MW/m which is the value for phase IV of CFETR (as shown in Table 3). This is roughly 50% larger than the expected values in EU-DEMO, $\sim$ 17 MW/m [9]. It will require an advanced divertor configuration (e.g. snowflake divertor or super-x divertor) and a technical improvement in the ability to remove heat from the divertor [2].

The on-axis field in the CFETR design is above that of EU-DEMO and the peak field on the conductor, 14.3 T, is above the ITER value, 11.8 T [10]. The current CFETR design assumes Nb_3Sn cable-in-conduit conductor (CICC), the same as ITER, and will have to provide structural support in excess of that of ITER to withstand the large stresses present given the larger field and current per turn while at a similar coil thickness.

The main area in which PROCESS was unable to match the CFETR design parameters is with regards to the value of q_{95} and the plasma current, I_p. PROCESS was able to reproduce the CFETR design point performance by two routes: i) low q_{95}, high I_p, low B_T, low n_e, high T_e design point, ii) a high q_{95}, low I_p, high B_T, high n_e, low T_e design point.

PROCESS was unable to exactly reproduce all the CFETR design point plasma parameters, which had the values $q_{95} = 5.5$, $I_p = 13.8$ MA, $B_T = 6.5$ T. However, it broadly reproduced the machine size, power output and engineering values. To achieve $q_{95} = 5$, PROCESS had to increase B_T to 7.2 T and subsequently $B_{T,max} > 15$ which is outside the allowed values for the maximum field. Given this the work that follows will focus solely on the lower $q_{95} = 3.5$ design point. A 1-D transport code is being implemented in PROCESS and will be useful in future work to have a self-consistent plasma model in PROCESS which will allow for better capturing the CFETR

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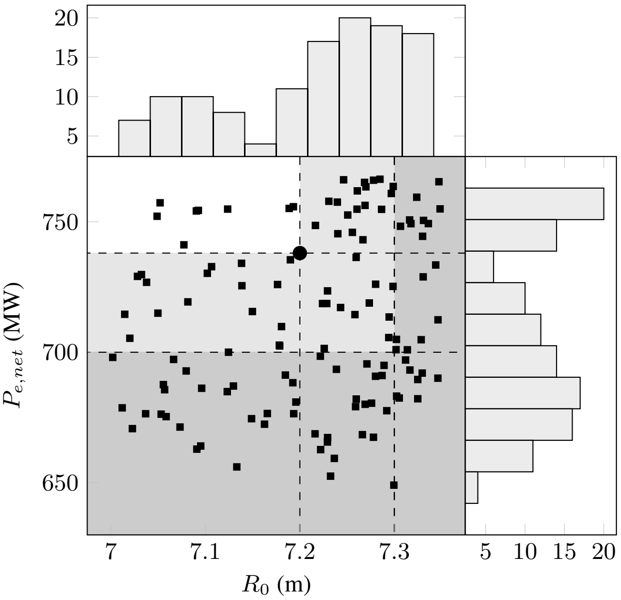

Figure 1: *Net electric power vs. major radius for the results of PROCESS using CFETR phase IV input file and applying uniform uncertainty distributions to a number of input parameters. The black circle is the phase IV CFETR design point and this plot shows 124 design points created by PROCESS. The non-shaded area shows points that exceed the phase IV performance and the lightly shaded area shows points that almost meet the phase IV performance.*

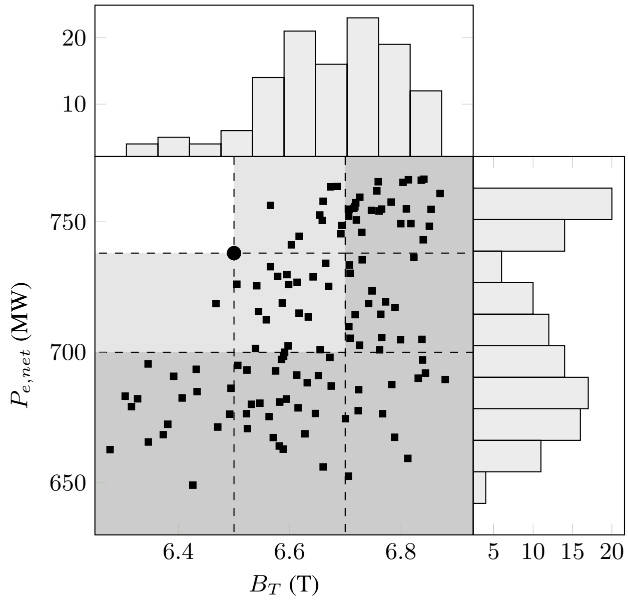

Figure 2: *Net electric power vs. on-axis toroidal magnetic field for the results of PROCESS using CFETR input file and applying uniform uncertainty distributions to a number of input parameters. The black circle is the phase IV CFETR design point and the plot shows 124 design points created by PROCESS. The non-shaded area shows points that exceed the phase IV performance and the lightly shaded area shows points that almost meet the phase IV performance.*

phase IV scenario [11]. Future work could re-run PROCESS with the output of a detailed plasma modelling code for the CFETR plasma scenario. The neutron wall load was limited to 2.3 MW/m^2 just above the value given for this CFETR design point of 2.23 MW/m^2. This value includes a peaking factor of 1.33. Including the peaking factor this neutron wall load equates to roughly 70% more than that of EU-DEMO, $\sim$ 1.3 MW/m^2. The PROCESS output is that of a steady-state machine which has no ohmic driven current. PROCESS doesn't capture information about the expected operational schedule of the machine or calculate the lifetime of in-vessel components which is required to calculate the duty-cycle. Even though the duty cycle of 30-50 % is one of the main goals of CFETR it is not covered here.

2.2 Phased design

As shown in Table 3 the CFETR design point in question has four phases of operation. One of the main challenges of a phased approach is to design plant systems capable of operating in a large parameter range. An example of this would be the tritium exhaust systems, which would operate in a large range of flow-rates and tritium inventory consistent with fusion powers of 120 MW to 2.2 GW. A machine of the scope of CFETR will require a long commissioning phase before full power operation and these phases can essentially fill that role as most of the machine (importantly the radial build) will not be changing between phases. This work focuses on phase IV.

3 Uncertainty Analysis - Inputs

After re-creating the CFETR design in PROCESS an uncertainty analysis was done to evaluate the robustness of the design when providing an input distribution for some input parameters. The uncertainty analysis focuses on the low-q_{95} ($q_{95} = 3.5$) solution from PROCESS. The uncertainty analysis was carried out using the PROCESS uncertainty tool (also used in [12, 13]). For these runs the figure-of-merit was to maximise the net electric power. The four parameters used in the uncertainty analysis are given in Table 2 and details given below.

The major radius, R_0, of a machine determines a large amount of the machine design as well as strongly driving the cost of the machine. One aim of the uncertainty analysis was to see if the main CFETR performance goals could be achieved with a machine which was smaller/larger than the phase IV design point given in Table 3. For this work R_0 was given the range, 7.0-7.4 m, with the CFETR phase IV value being 7.2 m.

The H factor is a measure of the plasma performance in H-mode. In PROCESS this value can be a fixed input or a free parameter. For this analysis the H-factor was given the range 1.1-1.42. PROCESS calculates the radiation corrected H-factor which is generally 0.1 higher than the non-radiation corrected H-factor [12].

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The on-axis toroidal field is a key parameter for machine design in PROCESS as when combined with the maximum allowable field it defines part of the machine size. The toroidal field for the uncertainty analysis was given the range 6-7 T.

The divertor protection parameter, P_{sep}/R_0 provides a 0-D/1-D code like PROCESS a method to take into account the need for divertor protection without having a fully detailed model of the divertor. For EU-DEMO the maximum protection parameter is $\sim$17 MW/m. For the given CFETR design point the value is 30.7 MW/m. For the uncertainty analysis P_{sep}/R_0 was given the range 20-40 MW/m.

4 Uncertainty Analysis - Output

The uncertainty analysis showed that given the uncertainties on the input parameters PROCESS was able to find feasible design points that met the goals of CFETR. For all of the runs the starting input was the same as the run described in §2. From the allowed parameter space PROCESS found 124 feasible design points. Of those design points there were 8 that exceeded the net electric power of the CFETR design point while being a machine of equal major radius or smaller. This is shown in Figure 1 by the non-shaded area. In Figure 1 the CFETR phase IV design point is surrounded by a number of feasible solutions in contrast to Figure 2 where it appears to be at slightly higher $P_{e,net}$ for the given on-axis field than the other solutions. Relaxing the targets of CFETR by a marginal amount results in a large increase in the number of feasible points found. Increasing the allowable R_0 by 1 % to 7.3 m and decreasing the required $P_{e,net}$ by 5 % to 700 MW_e results in 56 feasible design points (this is represented by the lightly shaded area in Figure 1). All 124 points resulted in a peak toroidal field less than the 14.3 T limit imposed on the runs. Figure 2 shows that none of the runs exceeded the net electric power output of the phase IV design point at a lower field. Reducing the requirements of $P_{e,net}$ as in Figure 1 and increasing the allowable on-axis field by 3 % to 6.7 T results in 30 feasible design points as shown in the lightly shaded area in Figure 2.

All 124 feasible design points are within the following parameter space:

- $P_{e,net}$ – 649 - 766 MW_e
- R_0 – 7.0 - 7.35 m
- B_T – 6.28 - 6.88 T
- H_{98y2} – 1.10 - 1.27
- Max B_T – 12.83 - 14.0 T

Most of the points in figures 1 and 2 would fulfil the CFETR high-level objectives. For example, just under 95 % of the design points (117) are within 10 % of the net electric power of the phase IV CFETR design point.

5 Summary

The work described in this paper has shown that PROCESS can broadly reproduce the CFETR design point, given some fixed user inputs, and finds a number of feasible solutions around that point that also satisfy the high-level objectives of CFETR. Using a small set of uncertainty parameters it was shown that PROCESS can find a collection of feasible design points around the phase IV reference. There are a number of assumptions made with the fixed user inputs that strongly impact the PROCESS output, such as high peak B_T, high divertor P_{sep}/R_0 and high H_{98y2}. These input assumptions can't currently be validated by a systems code but by the CFETR R&D program.

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