Benchmarking reactor systems studies by comparison of EU and Japanese system code results for different DEMO concepts

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Abstract:
Designing a fusion power plant requires balancing the interactions of many competing physics and engineering variables. A systems code is a program designed to self-consistently model the interactions of all the important sub-systems of such a plant and estimate the reactor operating windows. This paper reports recent work to benchmark and improve systems codes for the Broader Approach DEMO design. In general the codes are in good agreement but there are a number of outstanding issues including the flux swing calculations, the fast ion $\beta$ contribution, and impurity radiation. Work to improve modelling in these areas is discussed.

1 Introduction

On the path to commercial fusion power using magnetic confinement, it is necessary to consider what form a fusion power plant would take, bearing in mind achievable plasma parameters and engineering requirements such as magnetic field and peak divertor heat flux. These requirements are strongly dependent on the design choices for a conceptual power plant: the target net electric power; mode of operation; performance of superconducting magnets, and so on. A systems studies code is a computer program designed to integrate simple models of all important reactor systems, and thus calculate a self-consistent operating point (or use an optimisation algorithm to select a single such point from an operating window) for a fusion power plant which is possible to achieve given a set of initial physics and engineering assumptions, limits, and targets. This target operating window can then be used to guide physics and engineering development.

It is easy to appreciate that the models within a systems code may interact in complex and non-linear ways. It is therefore a useful exercise to benchmark independently-developed systems codes against one another and identify where they agree, and where
assumptions may be different, and such exercises are vital to have confidence in the reliability of the systems codes. Benchmarking work between the EU systems code PROCESS [1] and the Japanese systems code TPC [2] is ongoing and previous work has been reported [3].

In this paper we report recent work carried out under the Broader Approach and within the EU Power Plant Physics and Technology Systems Studies (PPPT-SYS) group aimed at stretching the models within the systems codes across a range of options. These were a conservative, pulsed DEMO design and an advanced, steady-state DEMO concept (Table I). The conservative DEMO design is intended to represent what might be achievable in the near-term, with minimal advances in physics and technology. The advanced DEMO concept is what may be possible with optimistic but foreseeable developments in tokamak plasma physics. For both devices Nb₃Sn superconductors and a 10 MW m⁻² divertor heat flux limit were assumed: both of these assumptions have strong effects on the resulting conceptual outcome. In the future it is intended to further quantify the effects of using high-temperature superconductor technology, allowing higher fields at the coils, in the advanced DEMO case. An example of the divertor technology assumptions is shown in figure 1. This graph shows the difficulty of reducing the calculated peak divertor heat flux Γ₆ᵥ below the assumed 10 MW m⁻² limit, and the reduction in machine size that would be possible if this limit could be increased. Additionally, increasing q₀, in these calculations, increases the bootstrap current fraction and reduces the auxiliary current-drive power required, demonstrating the advantages of advanced-physics scenarios. It is important to note that this work demonstrates the trends in outcomes, and that the absolute numbers may change as the modelling is improved. This is especially true for models with wide uncertainties such as divertor technology.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DEMOC</th>
<th>DEMOA</th>
</tr>
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<tbody>
<tr>
<td>R, a (m)</td>
<td>10.0, 2.5</td>
<td>8.0, 2.67</td>
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<tr>
<td>Pₖₑₑₑ (MW)</td>
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<td>2500</td>
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<tr>
<td>H, β₅₆</td>
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<td>2.5, 4.4</td>
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<tr>
<td>t_pulse (hr)</td>
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<td>∞</td>
</tr>
<tr>
<td>Pₐᵤₓ (MW)</td>
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<td>55</td>
</tr>
<tr>
<td>Z_eff</td>
<td>1.33</td>
<td>3.72</td>
</tr>
<tr>
<td>SC</td>
<td>Nb₃Sn</td>
<td>Nb₃Sn</td>
</tr>
<tr>
<td>Coolant</td>
<td>H₂O</td>
<td>He</td>
</tr>
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</table>

TABLE I: Basic parameters for “conservative DEMO” (DEMOc) and “advanced DEMO” (DEMOa). SC denotes superconductor technology assumed. H refers to the degree of energy confinement enhancement over the IPB98(y,2) scaling, \( H = \frac{τ_e}{τ_{IPB98}} \). The coolant affects assumed pumping power and thermal efficiency, and hence helps benchmark the plant power balance calculations.
FIG. 1: Calculated peak divertor heat flux as a function of \( Z_{\text{eff}} \) and major radius for DEMO\textalpha-type machines. For these data, \( q_0 = 2.0 \).

1.1 Systems codes

In essence a systems code must solve the plasma power balance equation in the core region

\[
\frac{dW_{th}}{dt} = P_\alpha + P_{\text{heat}} - P_{\text{rad}} - \frac{W_{th}}{\tau_E} = 0
\]  

(1)

where \( W_{th} \) is the plasma stored energy, \( P_\alpha \) is the heating power from the fusion-produced alpha particles, \( P_{\text{heat}} \) is the external heating and current-drive power, \( P_{\text{rad}} \) is the core radiation loss (including synchrotron, Bremsstrahlung, and line radiation), and \( \tau_E \) is the energy confinement time.

In addition the code is given various targets which must be achieved (such as fusion power) and technological limits (such as magnetic field on magnets). The code then tries to find a set of parameters \( \{n_e, T_e, R_0, I_p, \beta, \ldots\} \) which satisfy all these conditions and targets. The equation set is mostly described by the ITER Physics Design Guidelines: 1989 (IPG) \[4\] although PROCESS has later modifications \[5\].

The two systems codes used in this work differ substantially in operation. PROCESS takes a flexible set of variables and iterates numerically to find a solution. This allows the imposition of limits on the variables, and subsequent optimisation of the result in pursuit of a figure of merit (e.g. cost of electricity). However, unless a sensible starting point and limits are chosen, the solution may not converge. TPC, in contrast, has a fixed set of inputs and output variables: its solution may not meet the requirements imposed by technological limits. The two approaches are complementary and provide clues as to the right path to take to achieve a satisfactory overall solution. Despite the different solution methods, the results should agree if the underlying physics and technological assumptions are correct.

2 Recent benchmarking work

Earlier work has been reviewed elsewhere, many previously observed issues have been corrected \[3\], and the core physics of both codes now substantially agree. However, recent work also highlights a number of outstanding areas of disagreement. These are principally in the impurity radiation models and in the calculation of available flux swing for a pulsed reactor.
2.1 Impurity radiation

The radiation models are of particular importance since any advanced DEMO design must radiate a significant fraction of power (∼ 90% for an ITER-like divertor as modelled here) in order to protect plasma-facing materials in the divertor. This is the reason for the high $Z_{\text{eff}}$ in the advanced DEMO design – there is ongoing work on alternative divertor designs intended to ease this requirement. PROCESS and TPC handle this calculation in fundamentally different ways: PROCESS uses correlations obtained from transport simulations; TPC uses a coronal equilibrium model. In addition both codes use a simple parabolic form to represent the temperature and density profiles, with $n(\rho) = n_0 (1 - \rho^2)^{\alpha_n}$ and $T(\rho) = T_0 (1 - \rho^2)^{\alpha_T}$, where $n_0, T_0$ are the central density and temperature, $\rho$ is the normalised minor radius, and $\alpha_n, \alpha_T$ are peaking parameters. These forms are analytically tractable (giving volume averaged temperature $\langle T \rangle = T_0 / (1 + \alpha_T)$, for example), but do not include a representation of a pedestal nor a radiating “mantle” region, both of which are probably required to capture the details of impurity radiation behaviour.

However, there is little experimental data from such high radiation fraction regimes to calibrate the models, which still differ by 10-20%. The knock-on effects of this difference is discussed later. In particular, experiments into control of high levels of impurities in the plasma edge region, and the resulting spacial distribution of radiation from within the plasma, and the effects on global confinement time and the L-H transition are required, as are methods for extrapolating these data to DEMO environments.

2.2 Flux swing

Typically it is assumed that the majority of required flux swing is provided by the central solenoid, and the remainder is available from the vertical field coils. In this area as well, the calculations are approached in different ways by the systems codes and the correct calculation must be carried out. PROCESS calculates available flux swing from the mutual inductances of plasma and coils, whereas the TPC calculation is simpler.

The flux swing can be estimated (as TPC does), from

$$\Phi_{\text{avail}} \approx 2B_{\text{max}} \pi R_{\text{CS}}^2 + B_v \pi R_0^2$$

(2)

where $B_{\text{max}}$ is the maximum field on the central solenoid (CS), $B_v$ is the vertical field required by the plasma equilibrium, $R_{\text{CS}}$ is the radius of the CS and $R_0$ is the major radius of the plasma.

$B_{\text{max}}$ is a technological limit dependent on the materials used, and $B_v$ is given by

$$B_v = \frac{\mu_0 I_P}{4\pi R_0} \left( \ln \left( \frac{8R_0}{a} \right) + \beta_p + \frac{l_i}{2} - \frac{3}{2} \right)$$

(3)

Any more involved calculation should be close to this value. However, the discrepancy was too large to be ignored. On the other hand, both codes agree on the flux consumption of a particular plasma configuration.

As PROCESS invokes engineering limitations in its solutions, it attempts to calculate PF and CS coil positions, currents, and current densities. Assuming superconducting
coils, $B_{\text{max}}$ and $j_{\text{crit}}$ are set by the nature of the superconductor, and $I_{\text{CS}}$ is also limited by the cross-sectional area of the CS coil. It turned out that there was an error in the PROCESS calculations of the coil current waveforms. This calculation has now been rectified and is carried out as described below. The total available flux swing from the coil sets – and hence the pulse length – now agree well between the codes.

**PROCESS calculation**

PROCESS contains a magnetic field inverse solver which, given the magnetic field at a series of points and the location of a set of current loops, attempts to find the currents in the loops which give the magnetic field desired.

**Pulse initiation**

At the beginning of pulse it is assumed that the OH coil is fully charged with the maximum current density allowed. For the purposes of finding the currents in the PF coil set, the OH coil current is assumed to be represented by a user-specified number of filaments (default: 7). The magnetic field is defined to be zero at 32 equally-spaced points across the plasma mid-plane, and the solver is used to find the currents in the PF coils which are required to give this magnetic field.

If the total set of currents, including the OH coil current, is represented as $\{I_{\text{OH}}\}$ then it is clear that any scalar multiple $m \{I_{\text{OH}}\}$ of these currents will also have a magnetic field null across the plasma mid-plane. This configuration is listed in the PROCESS output as “CS coil field balancing”.

**Vertical field**

During the pulse a vertical magnetic field $B_v$ must be maintained to hold the plasma equilibrium. To find the PF coil currents required, the OH coil is now assumed to carry
Coil current envelopes

During start-up some of the required flux swing $\Phi_{\text{tot}}$ will come from the vertical field, and some from the CS. The remainder of the available flux-swing can be used to drive current during the flat-top phase.

As the vertical field is fixed by the equilibrium, the flux required from the CS coil during start-up is estimated from $\Phi_{\text{CS}} = \Phi_{\text{tot}} - \sum_i M_i \Delta I_{v i}$ where the sum is over the coil current set $\{I_v\}$.

From the magnetic field in a solenoid $B = \mu_0 N i / l$ we estimate the current swing required in the CS coil as

$$\Delta I_{CS} = \frac{\Phi_{CS} L_{CS}}{\mu_0 \pi \left( R_{CS}^2 + \frac{\Delta R_{CS}^2}{6} + \frac{R_{CS} \Delta R_{CS}}{2} \right)}$$

where $L_{CS}$ is the length of the CS coil, $R_{CS}$ is the CS bore, and the additional terms in the denominator correct for the finite thickness $\Delta R_{CS}$ of the CS coil.

If it is then assumed that at the initiation of a pulse the OH coil has its maximum allowable current $I_{\text{max}}$, and that this is indicated by $m = 1$, then the change in this scalar multiplier $\Delta m$ will be given by $\Delta m = \Delta I_{CS} / I_{\text{max}}$.

The current envelopes are then given by Table II.

### Table II: Current phases in PROCESS calculations.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Coil currents ${I_{\text{coils}}}$</th>
<th>$I_P(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 0$</td>
<td>${0}$</td>
<td>0</td>
</tr>
<tr>
<td>BoP</td>
<td>${I_{OH}}$</td>
<td>0</td>
</tr>
<tr>
<td>BoF</td>
<td>$(1 - \Delta m) {I_{OH}} + {I_v}$</td>
<td>$I_P$</td>
</tr>
<tr>
<td>EoF</td>
<td>$-{I_{OH}} + {I_v}$</td>
<td>$I_P$</td>
</tr>
<tr>
<td>EoP</td>
<td>${0}$</td>
<td>0</td>
</tr>
</tbody>
</table>

2.3 Fast ion $\beta$

TPC uses the linear (with $T_e$) fast ion $\beta$ contribution described in IPG, although with a high-temperature cut-off. PROCESS uses a fit based on $T_e^{1/2}$ (figure 3, left). These fits are based on the same underlying data [6]. As the $\beta$ limits in DEMO studies are usually
FIG. 3: (Left) Comparison of TPC and PROCESS fits for fast ion $\beta$ contribution as a function of density-averaged temperature for DEMO plasma densities. DEMOa has a plasma temperature of 20 keV, close to the point of maximum difference. (Right) Maximum pulse length configuration found by PROCESS as a function of major radius and $H$-factor for DEMOc-type machines.

applied to the thermal $\beta$, this does not have strong non-linear effects, but it is an area which requires further theoretical and modelling work, particularly if it is thought that the high fast-particle pressures expected in DEMO will have effects on stability.

3 Consequences

These discrepancies have numerous consequences. The radiation power affects the overall plasma power balance, resulting in a different stored energy ($W_{th}$, or manifesting as a different $\beta_{th}$) or different $H$-factor for otherwise similar scenarios. This may lead to a particular, otherwise acceptable, scenario being rejected as potentially unstable, or conversely may lead to investment of further work before the scenario is realised to be unrealistic. An illustration of the effects is shown in figure 3, right. Small changes in the $H$-factor ($=\frac{\tau_e}{\tau_{IPB98}}$), representing different enhancements of energy confinement, have a large effect on the size of machine required to achieve an 8 hour pulse length. The economics of a pulsed reactor depend on the pulse length, and so the calculation of this time is consequently of high importance. The models in the systems codes should be robustly checked. It is planned to overhaul the radiation models in the systems codes and, in PROCESS, to include mantle and pedestal models. It would be useful if high radiation fraction experiments were carried out to calibrate the models with reactor-relevant data.

The flux-swing calculation similarly has a strong effect on the economics of a pulsed reactor. We are now satisfied that the codes agree in this area, despite the differences in calculation methods.

The discrepancy in fast-ion $\beta$ contribution was uncovered when it was noticed that the thermal $\beta$ calculations agreed, but total $\beta$ differed. It is not well known what effects high fast-particle pressures will have in a DEMO-like plasma. More experimental data are needed.
4 Conclusions

The Broader Approach systems studies work has yielded valuable cross-checking of both systems codes, and has benefited PROCESS and TPC. Areas of extrapolation well beyond existing experimental data, for which the codes continue to disagree, have been identified. These areas – the effects of high fast particle pressure on $\beta$ limits, and the consequences of very high radiative fractions on confinement time (and the control of such radiating plasmas) – offer guidance for future experiments of direct relevance to achieving DEMO.

A major benefit of the PROCESS code is the inclusion of technology and economic models such as superconducting coils, cryogenics, costings etc. These systems impose additional limitations on the solution space, and TPC should move towards incorporating models of these systems. Future work will include development and benchmarking of these models, and further development of the advanced DEMO scenario.

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References


