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"PROCESS": A systems code for fusion power plants – Part 2: Engineering

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HIGHLIGHTS

- PROCESS is an optimising systems code for fusion reactors.
- It allows the user to choose which constraints to impose and which to ignore.
- Multiple constraints *greatly* restrict the parameter space of the optimised model.
- For example, when coil current is increased greatly, major radius hardly changes.

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ABSTRACT

PROCESS is a reactor systems code – it assesses the engineering and economic viability of a hypothetical fusion power station using simple models of all parts of a reactor system. PROCESS allows the user to choose which constraints to impose and which to ignore, so when evaluating the results it is vital to study the list of constraints used. New algorithms submitted by collaborators can be incorporated – for example safety, first wall erosion, and fatigue life will be crucial and are not yet taken into account. This paper describes algorithms relating to the engineering aspects of the plant. The toroidal field (TF) coils and the central solenoid are assumed by default to be wound from niobium-tin superconductor with the same properties as the ITER conductors. The winding temperature and induced voltage during a quench provide a limit on the current density in the TF coils. Upper limits are placed on the stresses in the structural materials of the TF coil, using a simple two-layer model of the inboard leg of the coil. The thermal efficiency of the plant can be estimated using the maximum coolant temperature, and the capacity factor is derived from estimates of the planned and unplanned downtime, and the duty cycle if the reactor is pulsed.

An example of a pulsed power plant is given. The need for a large central solenoid to induce most of the plasma current, and physics assumptions that are conservative compared to some other studies, result in a large machine, with a cryostat 36 m in diameter. Multiple constraints, working together, restrict the parameter space of the optimised model. For example, even when the ratio of operating current to critical current in the TF coils is increased by a factor of five, the total coil cross-section decreases only a little, because of the need for copper stabiliser, insulation, and structural support. The result is that the plasma major radius hardly changes. It is these surprising results that justify the development of systems codes.

1. Introduction

While physicists at experimental machines investigate whether a fusion plasma can be confined, it is equally important to assess whether a fusion plant is feasible from the engineering and economic points of view. Information on this is collated in reactor systems codes, which contain simple models of an entire power plant, including physics, engineering and costs. The PROCESS systems code has been used for many years, and details of its physics algorithms and general structure have been published previously [1]. This paper describes the engineering assumptions and models.

PROCESS is one of the most flexible of all reactor systems codes. It finds a set of parameters that maximise (or minimise) a Figure of Merit chosen by the user, while being consistent with the constraints, by adjusting a set of variables known as iteration variables. Both the constraints and the iteration variables are chosen by the user from an extensive selection. In effect, therefore, the user can

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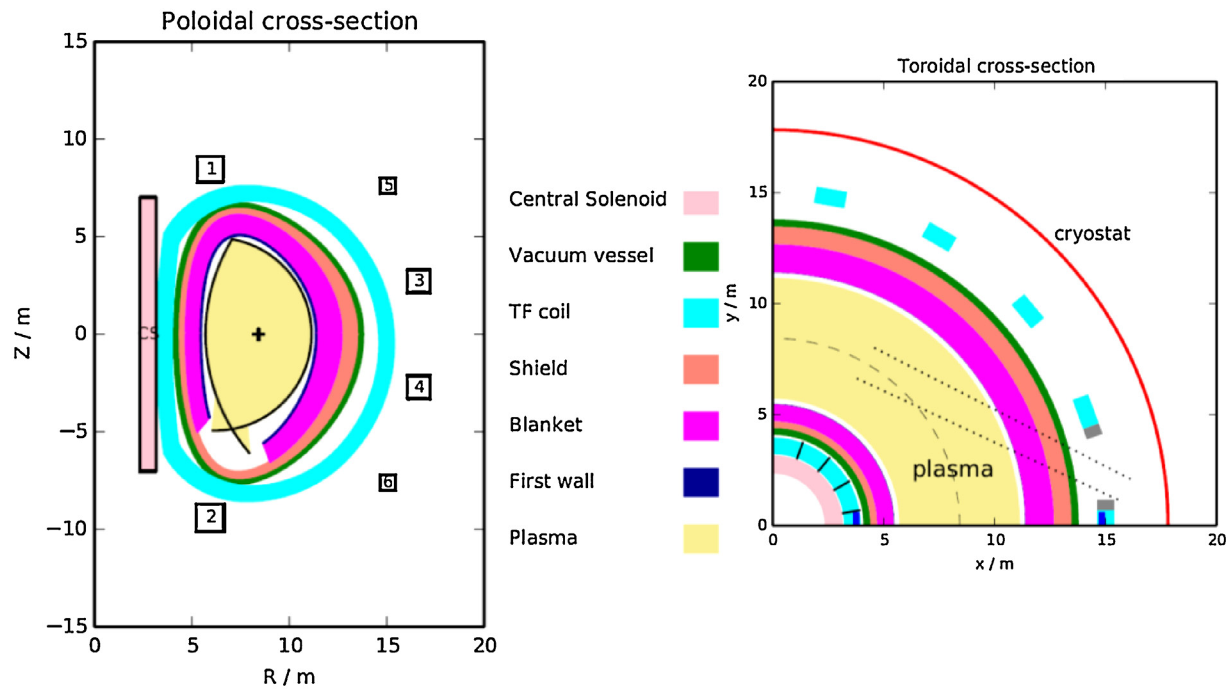

Fig. 1. Cross-sections of PROCESS model of a pulsed reactor. In one of the TF coils the winding pack is shown in blue, and the shielding for the neutral beam duct in grey. The thermal shielding which is needed to separate the cold superconducting coils from the hot reactor inside, and from the cryostat outside, is not included explicitly. The ports for diagnostics and remote handling are not shown because they are not modelled in PROCESS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

choose which are input variables and which are outputs. Only those constraints specified by the user are enforced. We describe PROCESS version 393.

Sections 2–8 describe the models for the superconducting magnets, the first wall, blanket and shield, the flow of thermal power and its conversion to electricity, and the availability model. Section 9 describes a pulsed DEMO model obtained using PROCESS, illustrated in Fig. 1.

2. Toroidal field coil (TFC)

In PROCESS the TF coil consists of a winding pack with a homogenous current density, surrounded by a structural case. Several conductor models are available, but the default assumes the use of forced-flow helium cooled superconducting cables, such as the cable-in-conduit type. AC losses are not taken into account. A number of constraints are available for the TF coil but, as always, are only enforced if selected by the user. They include: (a) stress in case, (b) stress in conduit, (c) ratio of operating current to critical current, (d) superconductor temperature margin, (e) quench voltage, and (f) quench temperature. Details are below.

Numerous input parameters are available as iteration variables, in which case PROCESS will vary them automatically, making them effectively outputs. These include the toroidal field on axis, the radial thickness of the TFC, the coil current per turn, the copper fraction in the conductor, the overall current density in TF coil inboard legs, and many others.

The TFC is symmetrical, each half being approximated by 4 circular arcs along the edge facing the plasma. The height is determined purely by the vertical build – the coil is not required to have a constant tension "D" shape. Note that the inboard leg is not exactly straight. This model is used only to calculate the mass, inductance and stored energy.

2.1. Access required for neutral beams

The maximum tangency radius for the neutral beams is determined by the size and shape of the TF coils, as the beams need to pass between them at an angle. This may be an important constraint on the achievable neutral beam current drive, as this is usually maximum when the tangency radius is equal to or slightly greater than the major radius [1,2]. Fig. 2 shows the geometry and symbols used. The need for remote handling may impose additional constraints. If the blanket modules run the full height of the machine, and are accessed for maintenance from above, then it would not be acceptable for a neutral beam duct to cut the whole blanket module in half, but this constraint has not been included

$$\Omega = \frac{2\pi}{N_{TF}} \tag{1}$$

$$F = \sqrt{\left(\frac{h}{2}\right)^2 + (L+b)^2} \tag{2}$$

$$H = \sqrt{L^2 + \left(\frac{h}{2}\right)^2} \tag{3}$$

$$\theta = \Omega - \tan^{-1}\left(\frac{h/2}{L}\right) \tag{4}$$

$$\phi = \theta - \tan^{-1}\left(\frac{h/2}{L+b}\right) \tag{5}$$

$$G = \sqrt{H^2 + F^2 - 2HF \ \cos\phi} \tag{6}$$

N_{TF} is the number of TF coils, and C is the width required for the neutral beam duct, including any shielding required to protect the TF coils on either side, the thickness of the duct wall, the thermal shields and the vacuum gaps.

$$J = \sqrt{G^2 - C^2} \tag{7}$$