Fusion Engineering and Design 89 (2014) 3054–3069

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

"PROCESS": A systems code for fusion power plants—Part 1: Physics

M. Kovari*, R. Kemp, H. Lux, P. Knight, J. Morris, D.J. Ward

CCFE, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

HIGHLIGHTS

- PROCESS is a fusion reactor systems code.
- It optimises a figure of merit subject to constraints chosen by the user.
- CCFE are working to make the assumptions and equations explicit and public.
- The PROCESS homepage is www.ccfe.ac.uk/powerplants.aspx.

ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form
11 September 2014
Accepted 18 September 2014
Available online 22 October 2014

Keywords:
Fusion reactor
Thermonuclear
Deuterium
Tritium
Economics

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, from the basic plasma physics to the generation of electricity. It has been used for many years, but details of its operation have not been previously published. This paper describes some of its capabilities. PROCESS is usually used in optimisation mode, in which it finds a set of parameters that maximise (or minimise) a figure of merit chosen by the user, while being consistent with the inputs and the specified constraints. Because the user can apply all the physically relevant constraints, while allowing a large number of parameters to vary, it is in principle only necessary to run the code once to produce a self-consistent, physically plausible reactor model. The scope of PROCESS is very wide and goes well beyond reactor physics, including conversion of heat to electricity, buildings, and costs, but this paper describes only the plasma physics and magnetic field calculations.

The capabilities of PROCESS in plasma physics are limited, as its main aim is to combine engineering, physics and economics. A model is described which shows the main plasma features of an inductive ITER scenario. Significant differences between the PROCESS results and the published scenario include the bootstrap current and loop voltage. The PROCESS models for these are being revised. Two new models for DEMO have been obtained. The first, DEMO A, is intended to be "conservative" in that it might be possible to build it using the technology of the near future. For example, since current drive technologies are not yet mature, only 12% of the current is assumed to be due to current drive. Consequently it is a pulsed machine, able to burn for only 1.65 hours at a time. Despite the comparatively large size (major radius is 9 m), the fusion power is only 1.95 GW. The assumed gross thermal efficiency is 33%, giving just 465 MW net electric power. The second, DEMO B, is intended to be "advanced" in that more optimistic assumptions are made. Comparison of DEMO A and B with a reference ITER scenario shows that current drive and bootstrap fraction need the most extrapolation from the perspective of plasma physics.

1. Introduction

Assessing the engineering and economic viability of a hypothetical fusion power station can best be done using a computer programme that includes simple models of all parts of a reactor system, from the basic plasma physics to the generation and transmission of electricity – in other words, a reactor systems code. These codes are well-suited to parametric studies and the identification of reactor operating regimes, which can then be more thoroughly investigated with more computationally intensive modelling methods. The Process code has been used for many years, in particular for the Power Plant Conceptual Study [1], but the details of its operation have not been previously published. This paper describes some of its capabilities in as much detail as is allowed by the space available, and the focus has been kept on the modules used for recent DEMO studies. It is hoped that the high

---

* Corresponding author. Tel.: +44 (0)1235 46 6427.
E-mail address: michael.kovari@ccfe.ac.uk (M. Kovari).

http://dx.doi.org/10.1016/j.fusengdes.2014.09.018

Table 1
Figures of merit. The iteration variables can be adjusted to maximise (or minimise) one quantity chosen from this list.

Capital cost (direct cost or constructed cost)
Cost of electricity
Divertor heat load
Neutron wall load
Plasma aspect ratio
Plasma major radius
Power injected by the heating and current drive systems
Pulse length
Ratio of fusion power to input power
Ratio of fusion power to power injected by the heating and current drive systems
Toroidal field on axis

level of detail in this paper will make it possible for the algorithms in Process to be evaluated and improved by collaboration with other institutions.

The code was based originally on TETRA (Tokamak Engineering Test Reactor Analysis) [2], which, together with much of the original version of Process itself, was written at Oak Ridge National Laboratory, with contributions from other U.S. laboratories.

PROCESS has two modes of operation. In the *non-optimisation mode* the code finds a single set of parameters that are consistent with the inputs and the specified constraints. It does this by adjusting a set of variables known as iteration variables. This solution is unlikely to be unique. In *optimisation mode* Process finds a set of parameters that maximise (or minimise) a figure of merit chosen by the user (Table 1), while being consistent with the inputs and the specified constraints. Given the large parameter space available, it is quite possible that the solution is a local rather than a global optimum, so it will depend on the starting values chosen.

It is useful to be able to scan through a range of values of a given parameter to see what effect this has on the machine as a whole. Scans are always carried out in optimisation mode. For the first run the iteration variables initially take the values specified in the input file, before being adjusted. In subsequent runs these variables are initialised to the values produced at the end of the previous run. The variable being scanned is incremented in each run. This method is intended to ensure that the machine parameters vary smoothly.

Because the user can apply all the physically relevant constraints, while allowing a large number of parameters to vary, it is in principle only necessary to run the code once to produce a self-consistent, physically plausible reactor model. The code does not need external routines or libraries. The user manual [3] explains not only how to use the code but how to add additional variables and equations, although it is intended to maintain a reference version of the code at CCFE. At present all users run a single version of the code on CCFE computers.

Many other systems codes have been developed – for example HELIOS [4], TREND [5] and SYCOMORE [6]. The scope of PROCESS is very wide and goes well beyond reactor physics, including pumping, conversion of heat to electricity, buildings and costs. This paper describes only the plasma physics and magnetic field calculations, and does not discuss current limits for superconductors, stress limits for coil structures, etc. (Part 2, a paper on the engineering and economic modules, is in preparation.) We describe Process version r326.

2. Options, constraints and code design

PROCESS has modules for many different basic fusion variants, including stellarators, inertial confinement, D-^{3}He fusion and hydrogen production. As this paper is focussed on the routines used for DEMO studies, only the well-developed conventional aspect ratio DT tokamak modules are described in this paper.

Table 2
Glossary of terms.

BOF	Beginning of Flattop
BOP	Beginning of Pulse
CS	Central Solenoid (ohmic heating coil)
Current drive	Methods for generating plasma current other than induced voltage and bootstrap current
EOF	End of Flat-top
Flat-top	Time during which the plasma is in an approximately steady-state, the plateau.
Flux swing	The change in magnetic flux linked by the plasma, equal to the time integral of the loop voltage
PF coil	Poloidal field coil (not including the CS)
Separatrix	Last closed flux surface, last closed magnetic surface
Shield	Radiation shield outside the blanket
TFC	Toroidal field coil

There are two types of constraints in PROCESS: consistency equations and inequalities. In the non-optimisation mode only the consistency equations are enforced. In the more commonly used optimisation mode, both consistency equations and inequalities are enforced. In both cases, only those constraints specified by the user are implemented. There are several hundred input parameters, but one hundred of these are available as iteration variables. The number of iteration variables chosen must be greater than the number of constraints. The optimisation routine varies the chosen iteration variables between specified bounds to optimise the figure of merit within the constraints. Any of the inequalities listed can be redefined as an equality by the user. For pulsed reactors, all quantities are evaluated at the highest value they reach during the pulse, unless otherwise stated. Only single and double-null divertor configurations (with one and two divertors respectively) are included.

The order of calculations is not always intuitive. The parameters whose initial values need to be defined at the start of the run include:

- electron density
- toroidal field on axis
- plasma size and shape
- profile indexes
- total plasma β
- fuel composition and impurity fractions
- safety factor at 95% surface, q_{95}
- Central Solenoid (CS) overall current density at the end of the flat-top burn period (EOF)
- density of hot ions due to input of energy from neutral beams
- The density of thermal helium ions as a fraction of the electron density

These parameters are available to be chosen as iteration variables, except for the thermal helium density.

3. Glossary and symbols

See Tables 2 and 3.

4. Plasma profiles

Two plasma profile options are available: without pedestal (the default), and a new model with a pedestal, which may be appropriate for an H-mode plasma. Not all the physics routines take account of the profile, however. The only models that use pedestal profiles in a fully self-consistent way are fusion power, lower hybrid current drive, and electron cyclotron current drive. The following models are based on specific profiles with no variable parameters: loop resistance, neutral beam shine-through and neutral beam