



FRESCO, a simplified code for cost analysis of fusion power plants



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HIGHLIGHTS

- FRESCO is a code for rapid evaluation of the cost of electricity of a fusion power plant.
- Parameters of the basic machine and unitary costs of components derived from ITER.
- Power production components and plant power balance are extrapolated from PPCS.
- A special effort is made in the investigation of the pulsed operation scenarios.
- Technical and economical FRESCO results are compared with those of two PPCS models.

ARTICLE INFO

Article history:

Received 20 June 2013

Received in revised form

17 September 2013

Accepted 23 September 2013

Available online 26 October 2013

Keywords:

Fusion power plant

Pulsed operation

Cost analysis

ABSTRACT

FRESCO (Fusion REactor Simplified Costs) is a code based on simplified models of physics, engineering and economical aspects of a TOKAMAK-like pulsed or steady-state fusion power plant. The experience coming from various aspects of ITER design, including selection of materials and operating scenarios, is exploited as much as possible.

Energy production and plant power balance, including the recirculation requirements, are derived from two models of the PPCS European study, the helium cooled lithium/lead blanket model reactor (model AB) and the helium cooled ceramic one (model B). A detailed study of the availability of the power plant due, among others, to the replacement of plasma facing components, is also included in the code.

The economics of the fusion power plant is evaluated through the levelized cost approach. Costs of the basic components are scaled from the corresponding values of the ITER project, the ARIES studies and SCAN model. The costs of plant auxiliaries, including those of the magnetic and electric systems, tritium plants, instrumentation, buildings and thermal energy storage if any, are recovered from ITER values and from those of other power plants.

Finally, the PPCS models AB and B are simulated and the main results are reported in this paper.

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1. Introduction

ITER will be the first fusion device with a reactor relevant Q value and extended burn. The principal physics goals will be to achieve inductively driven plasmas, with Q at least 10, for a range of operating parameters and to demonstrate steady state operations using non inductive current drive, with a Q at least 5. In order to reach these targets a reference physics operating scenario has been set up, namely the inductive operation scenario called ELMY H-mode. The recent theoretical developments of plasma scenarios, with active profile control and enhanced confinement regimes, represent a useful step forward towards DEMO and the

commercial power plant. In particular these enhanced regimes will offer the perspective of investigating also pulsed operations, i.e. with either purely inductive or “hybrid” current drive.

FRESCO (Fusion REactor Simplified Costs) is a computer code developed for rapid explorations of different scenarios, including the above mentioned inductive and hybrid operations, to be used as a tool for the conceptual designs of DEMO-like fusion stations. It is based on models for the evaluation of the physics, engineering and economical aspects of a TOKAMAK-like fusion power station, operating either in pulsed or steady-state options.

Whenever possible, technical and economical parameters are derived and extrapolated from those of ITER [1], while design and operation key features of the power station components, not included in ITER, are derived from the PPCS models [2]. In particular two different kinds of breeding blanket, namely the HCLL (Helium-cooled Lithium Lead) and HCPB (Helium-cooled Pebble Bed, ceramic/beryllium), are considered [3]. Finally, the structure

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of the economic module for the evaluation of the cost of electricity is largely based on that developed by the ARIES team [4] and on the SCAN model [5].

As described in Section 2, the main input data of FRESCO are the fusion power, aspect ratio, elongation, triangularity, temperature and density profiles, safety factor, maximum toroidal field at the coil conductors, blanket energy multiplication factor; hence the TOKAMAK inboard radial building can be computed. The plasma electromagnetic parameters including the β control through the Troyon factor are recovered as described in Section 3. In Section 4 the main parameters related to the type of operation (steady state or pulsed) are outlined, including the definition of the plant availability factor; the maximum allowable number of cycles in case of pulsed operation is also evaluated according to the S–N fatigue curves over the operational power plant life which is given as input. The magnetic flux balance and the thermal power balance equations are discussed in Sections 5 and 6. In particular the iteration procedures adopted to choose the operative parameters of the ramp up and flat top (heating plus burn) phases are described. Section 7 deals with the power balance break down of the power station. Finally, in Section 8 the economics of the power plant are discussed and the leveled cost of electricity for different operating options is recovered.

2. TOKAMAK radial build

The first step of FRESCO is the evaluation of the plasma minor radius starting from the fusion power (P_F , input datum).

The thermonuclear power (Eq. (1)) is a function of the square of fuel density, $n_{DT}(r)$, of the average reactivity $\langle\sigma v\rangle$ and of the energy released by a single D–T fusion reaction, ξ_{DT} (17.59 MeV).

$$P_F = \int_V \frac{n_{DT}(r)^2}{4} \langle\sigma v\rangle \xi_{DT} dV \quad (1)$$

The fuel density is computed from:

$$\frac{n_D + n_T}{n_e} = \frac{1}{Z - 1} \left(Z - Z_{eff} - 2(Z - 2) \frac{n_{He}}{n_e} \right) \quad (2)$$

by assuming equal deuterium and tritium densities (n_D and n_T respectively), fixed values for Z (charge of an impurity) and Z_{eff} (input datum) and setting a 10% helium fraction (n_{He}); the electron density n_e is an input datum as well.

Density, temperature and current profiles, $X(r)$, are assumed to have a parabolic dependence on radius:

$$X(r) = X_0 \left(1 - \frac{r^2}{a^2} \right)^{\alpha_X} \quad (3)$$

where X_0 is the value of X at the magnetic axis, r is the radial coordinate of flux surfaces ($0 < r < a$) assumed to have the same elongation k (input datum) and to be concentric. The values of the peaking factors of density and temperature, α_d and α_T are input data. The current peaking factor, α_j , is set $3\alpha_T/2$ [6]. Density and temperature values at the magnetic axis, X_0 , are derived from the respective average values ($\langle X \rangle$, input data):

$$X_0 = \langle X \rangle (1 + \alpha_X) \quad (4)$$

Where necessary, we consider the density weighted, volume-averaged plasma temperature, $\langle T \rangle_{dw}$, defined as follows:

$$\langle T \rangle_{dw} = T_0 \left(\frac{1 + \alpha_n}{1 + \alpha_n + \alpha_T} \right) \quad (5)$$

Note that we also assume that the electron and ion temperatures are equal, $T_e = T_i = T$.

The reactivity $\langle\sigma v\rangle$ is calculated by the Bosch and Hale formulation that ensures the correct evaluation throughout all temperature regimes:

$$\langle\sigma v\rangle = C1 \theta \sqrt{\frac{\xi}{m_r c^2 T(r)^3}} e^{-3\xi} \quad (6)$$

where the values of $C1$, ξ and $m_r c^2$ for a D–T reaction are taken from [7] and θ , which is function of temperature, is computed for each value of $T(r)$ according to the formulation reported in [7].

Finally, the plasma volume, V , is calculated as:

$$dV = (2\pi R)(A_f 2\pi k r dr) \quad (7)$$

where R is the plasma major radius and A_f is a multiplication factor, function of the plasma triangularity δ (input datum), thanks to which the plasma poloidal section area can be derived from the correspondent elliptic area. A_f is derived by a comparison of the elliptical area and the real plasma section area, the last calculated by using the parameterization of plasma boundary [8]. Defining R_0 as the radial distance of the plasma centre from the major axis of the torus, Z_0 as the vertical distance of the plasma centre from the torus mid-plane and δ , the coordinate of each point of plasma boundary are:

$$\begin{aligned} R(\theta) &= R_0 + a \cos(\theta + \delta \sin \theta) \\ Z(\theta) &= Z_0 + ka \sin \theta \end{aligned} \quad (8)$$

Therefore a fair approximation of the plasma poloidal section area is given by the sum of rectangles having a base of length $R(\theta + d\theta) - R(\theta)$ and a height of $Z(\theta + \delta d\theta)$.

By writing the integral as a summation and filling the volume equation (Eq. (7)), the fusion power equation (Eq. (1)) can be rewritten as:

$$P_F = \xi(2\pi A a)(2\pi k A_f) \sum_{r=0}^a \frac{n_{DT}(r)^2}{4} \langle\sigma v\rangle r dr \quad (9)$$

where A , the aspect ratio ($A = R/a$), is an input datum. This formulation allows the integral to be computed numerically being the fuel density and the reactivity calculated in each point of the plasma minor radius. Thus the value of a , the only unknown, is calculated through iterations. Once a is known, R is easily derived.

In order to calculate the average wall loading (W), defined as the ratio between fusion power and internal blanket surface (wall area, S_{wall}), the last is assumed to coincide with the external plasma surface, that is no scrape-off layer is accounted and the divertor surface facing to plasma is neglected. This hypothesis leads to overestimate the real wall loading. The plasma surface is calculated according to ARIES formulation [4] so that the plasma shape factor S (the ratio of the plasma poloidal perimeter, P_{plasma} , to the perimeter of a circular plasma with the same minor radius) is taken into account:

$$S_{wall} = (2\pi R)P_{plasma} = (2\pi R)(2\pi a S) \quad (10)$$

where S is:

$$S = \left(\frac{1 + k^2(1 + 2\delta^2 - 1.2\delta^3)}{2} \right)^{1/2} \quad (11)$$

The definition of the components which surround the plasma represent the second step of the FRESCO code. They are, starting from the plasma surface: first wall (FW), breeder, coolant tubes and manifolds, high temperature (HTS) and low temperature (LTS) shields, vacuum vessel (VV) and toroidal field coils (TFC). Each of them is characterized by different thickness depending on which part is considered (inboard or outboard). In Fig. 1 a layout of the inboard side of the machine is shown where dB , the blanket, is the sum of FW, breeding blanket and HTS, while dD and dC are the VV together with LTS and TFC thickness respectively.

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