Fusion Engineering and Design 87 (2012) 30–38

Contents lists available at SciVerse ScienceDirect

Fusion Engineering and Design

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

Generalized Lawson criterion for magnetic fusion applications in space

D. Petkow [a,*], R.A. Gabrielli [a], G. Herdrich [a], R. Laufer [b], H.-P. Röser [a]

[a] Institute of Space Systems, Universität Stuttgart, Pfaffenwaldring 29, 70569 Stuttgart, Germany
[b] CASPER, Baylor University, One Bear Place ♯97310, Waco, TX 76798-7310, USA

ARTICLE INFO

Article history:
Received 9 June 2010
Received in revised form 17 August 2011
Accepted 18 August 2011
Available online 20 October 2011

Keywords:
Fusion technology
Burn criterion
Nuclear fusion for spacecraft

ABSTRACT

In this work a generalized burn criterion for thermonuclear fusion reactors for space is derived. It considers not only the most important subsystems distinguishing terrestrial from astronautic magnetic confinement fusion technology but also features like a variable hot ion mode, a variable fuel ratio and a ratio coupling fusion product ions confinement time with energy confinement time. The modeling is based on a power density flux model. Solving the energy and particle balance equations for the triple product, an analytical expression for a more general burn criterion is obtained. The results for commonly studied reactant couples (D–T; D–^{3}He; ^{3}He–^{3}He; ^{11}B–p) for a given energy confinement time and a given fusion product confinement time ratio are presented. Based on that, an exemplary comparative system mass analysis is performed. Within the frame of a thermally heated fusion plasma with a hot ion mode <2, the assessment shows that the purely aneutronic ^{3}He–^{3}He reaction is most impractical for space applications and that there are important technological challenges to be met in the case of the ^{11}B–p reaction.

A generic system mass model is evaluated. Model improvements for future research activities are pointed out.

1. Introduction

Besides being investigated as a future option for a commercial energy source, nuclear fusion is proposed as a potential energy source for space applications. Both the application of fusion technology in propulsion systems and in power plants for large structures in near earth space have been considered since the dawn of the nuclear age [1].

Many advanced concepts of systems in near earth space lead to power requirements heavily exceeding the possibilities of conventional power systems. Conventional systems are also likely to fail in space beyond the orbit of Mars [2]. Some of them are too short lived or too feeble to sustain an appropriate power level. Especially the available density of solar power will decrease proportional to the inverse square of the rising distance to the sun. Only nuclear power systems such as radioisotope generators, fission, or fusion reactors appear to be viable.

Concepts for fusion powered space propulsion have been studied since the 1950s. Most prominent are proposals based on various geometrical configurations of magnetic confinement fusion, summarized in [1]. The configurations include among others Spheromaks [3], Tandem Mirrors [4], Field Reversed Configurations [5,6], and Kammash's Gasdynamic Mirror [7,8]. The key difference between these concepts and terrestrial reactor types like Tokamak and Stellarator [9] is the magnetic field line configuration. Typical confinement concepts for propulsion are in general conceived to be *open* in the sense that either fusion plasma can be extracted from some opening in the confinement or a fluid is considered to be heated up by bringing it closer to the energy source. Another aspect the researches addressed was the qualification of different fusion reactions against typical requirements. The most pertinent reactions are

$$\begin{aligned} \mathrm{D} + \mathrm{T} &\rightarrow \mathrm{n} + {}^4\mathrm{He}, \\ \mathrm{D} + {}^3\mathrm{He} &\rightarrow \mathrm{p} + {}^4\mathrm{He}, \\ {}^{11}\mathrm{B} + \mathrm{p} &\rightarrow \gamma + 3{}^4\mathrm{He}, \\ {}^3\mathrm{He} + {}^3\mathrm{He} &\rightarrow 2\mathrm{p} + {}^4\mathrm{He}. \end{aligned}$$

Recent research [10,11] concerned the latter as well as the identification of the most promising fusion technology for application in space by elimination of options [10–12]. In this context the need of a more precise burn criterion enabling the study of various subsystems' impact had to be met.

There have been several attempts to extend the original burn criterion. In 1975 Maglich and Miller introduced a burn criterion which is based on, e.g. the characteristic time scale for reaction kinetics τ_R and which included various non-radiative losses [13]. This approach was criticised by Chen et al. [14] because the use of

* Corresponding author. Tel.: +49 711 68562412; fax: +49 711 68563596.
E-mail address: herdrich@irs.uni-stuttgart.de (G. Herdrich).

0920-3796/$ – see front matter © 2011 Published by Elsevier B.V.
doi:10.1016/j.fusengdes.2011.08.008

the energy confinement time τ_E already covers the losses by other means than radiation.

The present work respects this fact. It also considers the impact of fusion ashes; the product ions' confinement time is used for this aim. Further, since it addresses other than the classic D–T reaction also three advanced reactant couples, losses due to synchrotron radiation are to be considered. The criterion also needs to allow for studies concerning the effects of an assumed hot ion mode operation and thus an estimation of the use of further development. Similar considerations lead to account fuel mixing ratio and recirculation parameters k. Given these considerations, an extended burn criterion with the following main features is introduced:

- The energy confinement time τ_E is used.
- A ratio $\tilde{\tau}_{Ea}$ is coupling the fusion product ions' confinement time τ_a to τ_E.
- Synchrotron radiation is taken into account.
- Hot ion mode ϕ as well as the fuel mixing ratio ψ are considered.
- Radiation type dependent reflection and absorption properties can be defined explicitly.
- Side reactions are neglected.

The present article summarizes the derivation of the criterion according to the indicated requirements. In the second section, the major challenges of space environment are presented and the main differences between terrestrial and space based fusion reactors as well as resulting consequences are highlighted. Fusion powered propulsion is introduced. The generic model of our studies and its most pertinent subsystems are briefly described. In Section 3, power definitions for the considered phenomena are summarized. These definitions are as general as possible to allow studies of various parameters. The energy balance equation is solved yielding an implicit analytical expression for the triple product $n_i \tau_E T_i$ of ion density n_i and energy confinement time. Lawson's criterion is obtained from the generalized criterion by inserting classic assumptions and parameters of the D–T reaction. In the last section, results gained from the criterion are briefly indicated.

2. Magnetic confinement fusion systems for space applications

There are two main purposes for energy in space flight: feed-in for gear and propulsion. The latter is more exigent than the earlier and early space flight pioneers already concluded [15] that this exigency makes nuclear power provision extremely attractive. Space faring systems including Nuclear Electric Propulsion (NEP) [16] – including fusion electric propulsion – and thermal propulsion among which Nuclear Thermal Propulsion (NTP) – among which finally fusion thermal propulsion and especially Magnetic Confinement Fusion (MCF) propulsion – have more demanding requirements than terrestrial applications. Apart from mass limitations there are exigencies concerning the power management, most notably the existence of a proper waste heat dump. Also, one needs a highly efficient generation of usable power. Thus, fusion reactors in space will look different from those on earth and will have to be equipped with additional subsystems such as radiators. In [1] and in the following, energy conversion, blanket, magnets, cryoplant, and minor auxiliaries are discussed. Each of these subsystems has a certain impact on the overall power flux of a fusion reactor.

2.1. Generic 1D model

For the sake of simplicity it is assumed that the core of the thermonuclear fusion reactor is the hot plasma around which the hardware is build. The plasma is confined by magnetic fields. For

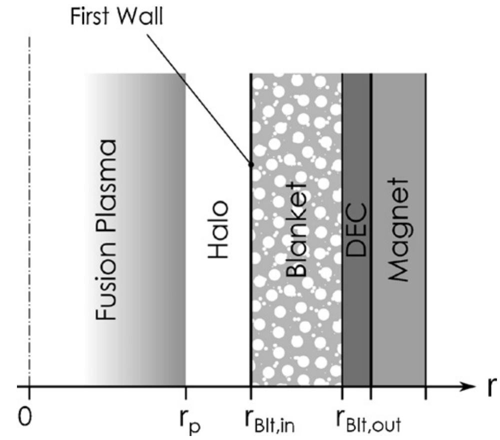

Fig. 1. Arrangement of the assumed one-dimensional reactor's components. Radiators are not shown.

preliminary studies a simplified spherical and leak proof configuration is assumed. There is no contact of plasma with the vessel's first wall. Similar to a terrestrial reactor, the blanket is situated beyond the first wall and its outer boundary may be covered with direct energy conversion (DEC) systems. Waste heat will be transported to a system of radiators. The concept is idealized to a one dimensional model as shown in Fig. 1.

2.2. Blanket

Apart from optional breeding subsystems like their terrestrial counterparts for the D–T reaction, the blankets in spaceborne fusion reactors may have another important function probably occurring in fusion powered propulsion systems: the heat exchange between the fusion system and the coolant/propellant. One of the discussed thermonuclear reactor designs for space propulsion applications considers a porous blanket with coolant ducts [12].

2.3. Energy conversion systems

The DEC can be used to provide electrical power to the space system. Excess of electrical energy may be either stored, consumed by other systems, or fed back into the plasma in order to provide additional heating if necessary.

2.4. Magnets

The magnets provide the magnetic fields which are strong enough to enable an adequate plasma confinement.

2.5. Radiators

One of the major differences between the space and the terrestrial environment is the absence of a surrounding gas. Heat transfer by convection will generally be negligible. Thus, the only way to dump waste heat is radiation. A thermonuclear fusion reactor in space will need like any other power generation system an adequate system of radiators to ensure a sustainable power management.

3. Energy balance equation

To assess the feasibility of a fusion reactor, its response to adequate burn criteria has to be studied. Lawson [17] derived the criterion named after him from the energy balance equation. The energy terms which contribute to this equation in the present case