Fusion Engineering and Design 91 (2015) 52–59

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

The use of water in a fusion power core

M.S. Tillack[a,*], P.W. Humrickhouse[b], S. Malang[c], A.F. Rowcliffe[d]

[a] University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093, United States
[b] Idaho National Laboratory, PO Box 1625 MS 3840, Idaho Falls, ID 83415, United States
[c] Fusion Nuclear Technology Consulting, Fliederweg 3, 76351 Linkenheim, Germany
[d] Oak Ridge National Laboratory, Oak Ridge, TN 37831, United States[1]

ARTICLE INFO

Article history:
Received 21 August 2014
Received in revised form
18 December 2014
Accepted 21 December 2014
Available online 16 January 2015

Keywords:
Blankets
Divertors
Power plants

ABSTRACT

Water has both advantages and disadvantages as a coolant in conceptual designs of future fusion power plants. In the United States, water has not been chosen as a fusion power core coolant for decades. Researchers in other countries continue to adopt water in their designs, in some cases as the leading or sole candidate. In this article, we summarize the technical challenges resulting from the choice of water coolant and the differences in approach and assumptions that lead to different design decisions amongst researchers in this field.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Water is a common coolant used in existing fission reactors throughout the world. A large base of operating experience has been accumulated for heat exchangers, steam generators, chemistry control and other large-scale water systems. There are issues with the use of water in fission reactors, like stress corrosion cracking or steam generator tube wear, but those issues are mostly known and addressed in designs.

Advanced "Gen IV" fission reactor concepts also have been studied for many years [1]. These concepts are pursued because they offer substantial improvements in safety, waste, economics and/or non-proliferation while still considered feasible in the near term (mid-21st century time frame). Most Gen-IV fission reactor concepts rely on alternative coolants, including helium, molten salt and liquid metal to obtain their advantages. One remaining candidate uses supercritical water.

In any case, our experience with fission reactors may have only limited applicability to fusion. For over 30 years, conceptual studies for fusion power plants have described a wide range of design options that include the choice of primary coolant. *Within the US*, water has been avoided in conceptual fusion power plant design studies for over 25 years as a result of factors related to performance and safety. The purpose of this paper is to explain the technical and programmatic reasons for avoiding water within the fusion power core.

Design choices involve complex relationships between materials and systems, and also depend strongly on the design *requirements* applied to any particular facility. Unfortunately, we do not have a modern self-consistent US power core design using water to allow an integrated evaluation. While each study must address its own choices in an integrated and self-consistent fashion, here we attempt to generalize the rationale for excluding water based on our experience in several ARIES power plant studies performed over the past 25 years. We restrict our attention to "in-vessel" blanket and divertor components and the vacuum vessel. The choice of heat transport fluid for the power conversion cycle is an important related topic, but is not discussed here.

Besides purely technical attributes, it is important to understand the role of programmatic factors in the design of future energy systems. For example, in some parts of the world, government-sponsored research is aggressively trying to compress the timeline for a demonstration of practical fusion energy by mid-century. The technical readiness of the primary coolant system today is therefore an important factor in decision-making, and economic competitiveness may play a lesser role. In the US, the Department of Energy supports a basic research program with the goal of resolving the major science and technology challenges for practical and competitive fusion energy. The existence of remaining R&D needs is considered acceptable, and forms the basis to plan the research portfolio. In either case, whether driven by a near-term sense of

* Corresponding author. Tel.: +1 858 534 7897.
E-mail address: mtillack@ucsd.edu (M.S. Tillack).
[1] Retired.

http://dx.doi.org/10.1016/j.fusengdes.2014.12.013
0920-3796/© 2014 Elsevier B.V. All rights reserved.

urgency or a long-term vision, fusion is a speculative future energy source without a clear customer nor an obvious market potential in the US. For that reason, we must maintain focus on the attributes of a fusion energy system that could lead one day to its implementation within the US.

This paper is not meant to render a broad judgment on the suitability of water as a coolant for every application. Design choices depend on many factors that include both technical and non-technical issues. Alternative coolants, such as helium, liquid metals and molten salts each carry their own issues and limitations. Only in the context of an integrated design study with specific project requirements can coolants be compared in a quantitative fashion and a suitable candidate selected.

2. Previous design studies

Existing designs of fusion facilities generally fall into one of two categories: (1) conceptual designs of long-term visions for a power plant, and (2) detailed engineering designs for experimental facilities like ITER. Recently, especially in Europe (EFDA) and *via* the EU-Japan Broader Approach activities, increased attention has been given to near-term implementations of a fusion power plant demonstration [2,3]. Although still in an early pre-conceptual phase of study, this machine is intended to proceed through a detailed engineering design phase and construction in the mid-21st century time frame. In the US, an activity was started in 2014 to explore the mission space and requirements for a fusion nuclear test facility called Fusion Nuclear Science Facility (FNSF), leading to its possible construction. FNSF is a plasma confinement facility whose purpose is to bridge the gap between ITER's plasma and nuclear environment and that of Demo [4].

In this section, we summarize the long-term concepts developed by the ARIES Team, the design choices made for the near-term ITER burning plasma experiment, and finally documentation from Europe and Asia on their power plant and Demo concept selection processes. These projects all have their own unique goals and ambitions, which affect the design selection process decisively.

2.1. ARIES power plant studies

Design decisions are usually derived from the evaluation of alternative concepts relative to some set of metrics or requirements. Although the requirements for a new source of nuclear energy in the future are uncertain and evolving, it is important to establish a quantitative basis for decision-making; otherwise, decisions can be biased by individual judgment or political pressure. In 1994, an advisory group was formed to provide guidance on the criteria for practical fusion power systems from a US electric utility industry perspective [5]. These relate to economics, public acceptance and regulatory simplicity. Following that, top-level design requirements were derived at a level of detail needed to support continuing design studies [6]. The requirements and attributes of an attractive power plant that impact these requirements are summarized in Table 1. These requirements have formed the basis for design decisions in US conceptual fusion power plant studies ever since they were introduced.

In the years following the establishment of utility-inspired requirements, the ARIES team carried out studies of several different magnetic confinement configurations for electric power plants in the range of 1 GW net electric output. These include a stellarator (ARIES-CS [7]), low aspect-ratio tokamak (ARIES-ST [8]), and several moderate aspect ratio tokamaks (A = 4) covering a wide range of design space (ARIES-AT [9] and ARIES-ACT [10]). In those designs, PbLi became the preferred breeder. Both self-cooled and dual cooled (PbLi and He) blanket designs were explored. Divertor designs were developed using PbLi (at lower heat flux levels) or helium. Water has not been adopted for use inside the vacuum vessel in an ARIES study in over 2 decades.

Table 1
Technical requirements and attributes of an attractive fusion power plant.

Requirements	Example attributes
Cost advantage over other available options	High thermal conversion efficiency, high component efficiencies, compact (high beta), low recirculating power (*e.g.* high bootstrap fraction), high availability, uncomplicated components with low cost fabrication
Eased licensing process	Plant standardization, low activation materials, low energy release potential, low tritium inventory
No need for evacuation plan	Low activation materials, low energy release potential, passive safety, reliable containment, low tritium inventory
Produce no high-level waste	Materials choices
Reliable, available, and stable	Ample design margins, uncomplicated designs, fast and easy maintenance
No local or global atmospheric impact	Low CO_2 emissions, low tritium emissions
Fuel cycle is closed and on-site	Controllable tritium generation; efficient generation, extraction and processing of tritium; tritium control and barriers to losses
Fuel availability is high	
Plant is capable of operation at partial load	
Plant is available in a range of unit sizes	

2.2. The ITER experiment

ITER is an experiment, now under construction, that is expected to demonstrate the creation and control of a burning plasma in the tokamak configuration. Many of the technologies required for a tokamak power plant, such as superconducting magnet systems and tritium fueling systems will be demonstrated at power plant relevant scale. The base blanket does not breed tritium and does not operate at a temperature capable of generating electricity. Small ports allow in-vessel testing of more reactor-relevant technologies for blankets [11]. The total accumulated neutron fluence will be much lower than required in a power plant. The lower fluence and reduced requirements on the base blanket enable the use of more established technology choices.

Water has been selected as the coolant for all in-vessel components of ITER. The blanket and divertor normally operate with inlet water temperature of 70 °C and 4 MPa pressure [12]. The outlet temperature is typically ∼50 °C higher than the inlet.

The structural material for all in-vessel components is 316L(N) austenitic steel. This steel is in direct contact with the water coolant within the blanket, whereas a copper alloy is used for the heat sink in the divertor target plates. Both 316SS and copper alloy are compatible with the use of low temperature water coolant in ITER. However, at the higher required operating temperature and higher fluence of a power plant, both of these materials are expected to suffer severe property degradation. In order to use water in a power plant, either alternative materials must be utilized or the performance and safety requirements of the device must be reduced. These issues are described in more detail in Section 3 of this report.

The water coolant in the ITER divertor target plates, which are composed of W as plasma facing material and a Cu-alloy as heat sink material, flows in specially designed small cooling channels,

Download English Version:

https://daneshyari.com/en/article/271024

Download Persian Version:

https://daneshyari.com/article/271024

Daneshyari.com