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Evaluation of a power plant concept for fast ignition heavy ion fusion

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Abstract

The characteristics of a fast ignition heavy ion fusion (FIHIF) power plant are preliminarily evaluated. The reactor chamber consists of two sections: The upper smaller part is the microexplosion section proper; the lower bigger part is the condensation section, in which sprayed jets of coolant are injected. The first surface of the blanket is of generally accepted wetted porous design. The coolant is lithium-lead eutectic with an initial surface temperature of 820 K. The mass of the evaporated coolant just after the explosion is evaluated as 4 kg. Computation of neutronics results in blanket energy deposition with maximum density of the order of 10^8 J/m^3 at the first wall. The heat conversion system consisting of three coolant loops provides a net efficiency of the FIHIF power plant of 0.37.

Keywords: Inertial heavy ion fusion; Power plant; Reactor chamber

1. INTRODUCTION

There are a number of power plant concepts for inertial fusion energy. The most detailed conceptual design was developed for the HIBALL-II (Badger *et al.*, 1984) and LIBRA (Badger *et al.*, 1980) projects. The major systems of the plant are configured in OSIRIS (Bourque *et al.*, 1992), PROMETEUS-H (Meier & Waganer, 1993), HYLIFE-II (Moir *et al.*, 1994), and the other projects (Hogan, 1995). The heavy ion driver and multisided target illumination are employed in many projects (Badger *et al.*, 1984; Bourque *et al.*, 1992; Meier & Waganer, 1993). As a rule, a wetted wall for the reactor chamber is used. One-side illumination by heavy ion beams design is considered in the HYLIFE-II project. The energy conversion systems including fuel cycle the data on IFE plant layouts, output characteristics, and economics are discussed.

In this article, a preliminary conceptual evaluation of power plant systems for fast ignition heavy ion fusion is done. The hydrodynamic scenario of the fast ignition of a cylindrical target is described by Basko *et al.* (2002). In this article, the following output parameters of the target are assumed: gain of 100, X-ray energy release of 50 MJ, ion debris energy of 100 MJ, and neutrons energy of 350 MJ per shot. The total target mass equals 4.56 g. The high power heavy ion driver accelerating multimass platinum ions of negative and positive charges is analyzed in Koshkarev *et al.* (1996). The heavy ion driver produces two beams: the compressing hollow beam with an energy of 4.6 MJ and a duration of 60 ns, and the ignition beam with an energy of 0.4 MJ and a duration of 0.2 ns. The efficiency of the driver is taken as 0.25. The reactor chamber design with wetted wall has an extended volume in which the coolant condensation occurs at the dispersed jets. The energy conversion system consists of three loops with $Li_{17}Pb_{83}$, Na, and H_2O coolants.

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2. REACTOR CHAMBER

For the reactor chamber of a FIHIF power plant, a wetted wall design was chosen. A comprehensive review of liquid wall design principles is made by Moir (1996). A geometrical configuration of the reactor chamber is worked out as a compromise among contradictory demands of a permissible energy loading of the first wall and the blanket, a minimum period of the chamber clean-up from vapor and droplets of coolant, and reasonable distance between the target and the focusing magnets. This means, that on the one hand, the distance between the first wall and the target is to be as small as possible and, on the other hand, the volume of the chamber and the liquid surface for vapor condensation has to be quite large. Under these conditions, it is worthwhile to accomplish the microexplosion and the condensation in separate spaces. This can be arranged by making the reactor chamber of two adjacent sections (Fig. 1).

The upper section is the explosion chamber itself. The lower section is an auxiliary volume for the condensation of vapor on sprayed jets. The diameter of the upper section is 6 m. The coolant is eutectic $Li_{17}Pb_{83}$. The parameters of the atmosphere in the reactor chamber are taken under restrictions of the Pt ion beam deterioration during its traveling in the cavity of the chamber. The vapor density is equal to 10^{18} m^{-3} at a coolant temperature of 820 K (Moir, 1996). The first wall and the blanket are of conventional design. The liquid film is formed at the SiC porous wall. In the blanket, the tubing is made of vanadium alloy. The construction wall of the chamber is manufactured of steel of HT-9 type. We prefer SiC and vanadium alloy because of their better thermoelastic and anticorrosion properties (Zinkle, 1998).

3. THE CHAMBER RESPONSE

An impact of a microexplosion on the chamber wall includes X-ray, debris, and neutrons fluxes. X-ray radiation causes evaporation of the liquid film at the first wall surface. An instantaneous X-ray deposition in $Li_{17}Pb_{83}$ liquid film is characterized by an energy density of $Q = 3 \times 10^5$ J/m^2 and an attenuation length of $l = 10^{-6}$ m. According to the method described in the HIBALL-II project (Badger *et al.*, 1984), the estimation of the evaporated layer thickness δ is given by $\delta = 3.8 \cdot 10^{-6}$ m and the mass of the vapor is approximately equal to 4 kg.

For estimation of the parameters of debris arriving at the first wall we use the asymptotic Sedov solution for a spherical fireball expanding into vacuum (Sedov, 1954). According to Sedov, the debris front U, density ρ, and time of arrival τ are estimated as follows: $\tau = 10^{-5}$ s, $\rho = 5 \times 10^{-5}$ kg/m^3, $U = 2.7 \times 10^5$ m/s. Deceleration of the debris at the wall occurs in a reflected shock. Instantaneous pressure behind the shock p_s is evaluated as $p_s = 5 \times 10^6$ Pa. The impulse transmitted to the wall is equal to $I = 2.7$ Pa·s.

The evaporated layer of $Li_{17}Pb_{83}$ fully absorbs the debris ions, since the Bethe–Bloch approximation of Pb ion energy losses shows that the stoppage range is much less than the thickness of the evaporated layer of liquid. Therefore it can be supposed that the evaporated layer is additionally superheated by debris ions. The evaluated resulting temperature of the vapor amounts to 27.5 eV (i.e., 3×10^5 K). The process of condensation is considered to start with this initial temperature of vapor. It is assumed that the vapor temperature and density are uniform in the volume of the reactor chamber and sharp change of the vapor parameters occurs in this layer at the first wall. In this case, the surface condensation and vaporization can be described by kinetic relationships (Isachenko, 1972). For the chamber geometry, given above (Fig. 1), the results of computation of the condensation rate are shown in Figures 2 and 3. The vapor density practically reaches the saturation value at 0.017 s. This in-

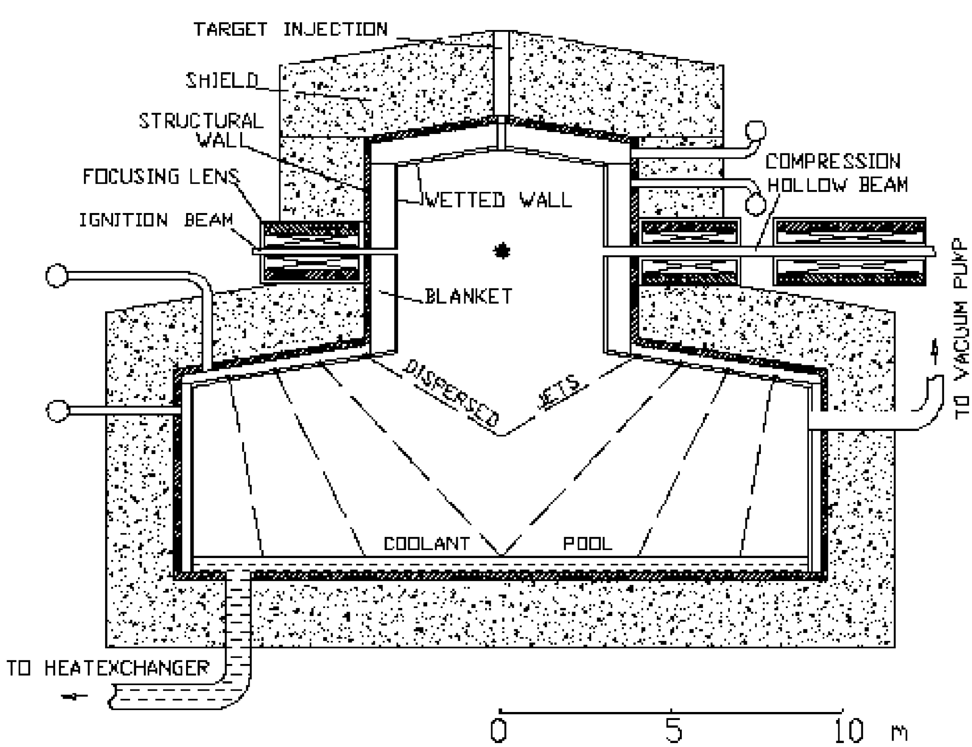

Fig. 1. Reaction chamber for FIHIF concept.

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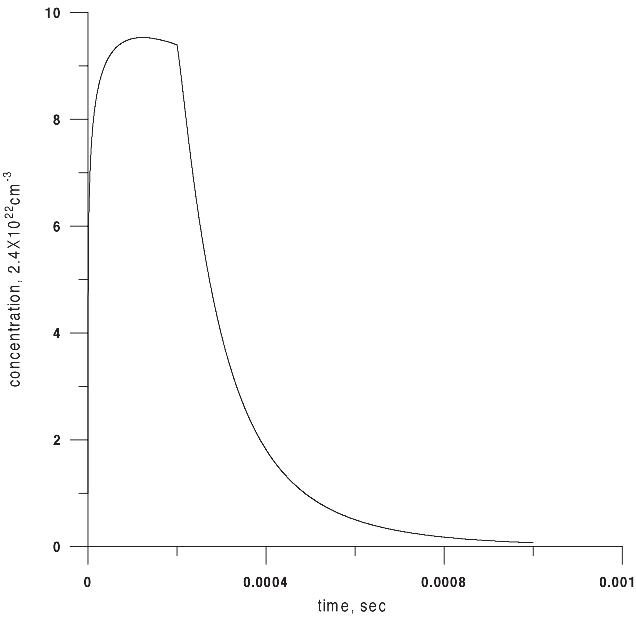

Fig. 2. Vapor concentration in the chamber versus time.

dicates that in our model, the condensation process does not limit a repetition rate of shots. But bearing in mind that thin liquid layer behavior may be accompanied by liquid droplet dispersion, the lower repetition rate of 2 Hz is taken.

The two-dimensional calculations of neutron transport in the blanket with the use of the MCNP code (Group 6, 1981) resulted in high-energy release in the materials. In the first wall zone, the energy density amounts to 50 MJ/m^3. This leads to a pressure vise in the material of the order of 100 MPa. The unloading of the material in the compression tension wave, traveling from the free surface of the first wall in to the blanket structure, may produce tension stress of 50 MPa. The yield strength of SiC and vanadium alloy at a temperature of 820 K are σ_Y (SiC) = 70 MPa and σ_Y (V) = 250 MPa (Zinkle, 1998). These values are given for nonirradiated samples under stationary conditions. The neutron radiation and the cycling loading can change the material strength, which is a concern in the blanket design.

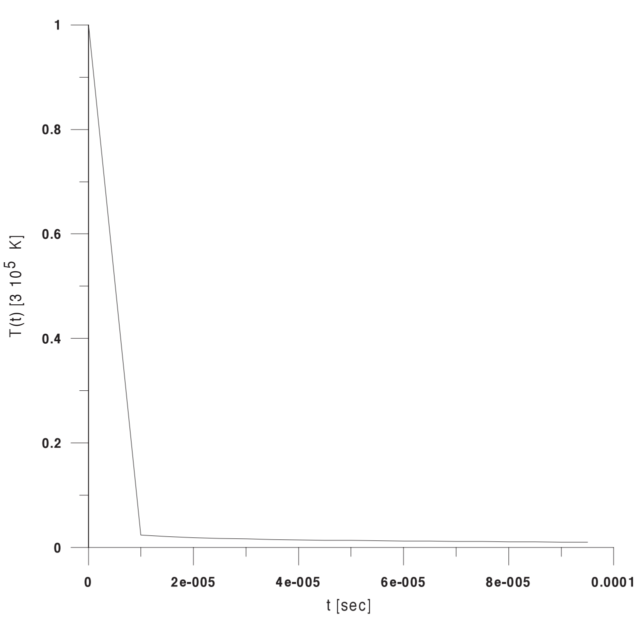

Fig. 3. Vapor temperature in the chamber versus time.

4. ENERGY CONVERSION SYSTEM

The energy conversion system consists of three loops (Fig. 4). The coolant of the second loop is sodium. The third loop is a steam turbine cycle. The principal parameter of the system is the maximum temperature of $Li_{17}Pb_{83}$ at the outlet of the reactor chamber. It is taken as 823 K. The inlet temperature of the eutectic is equal to 623 K. The temperature drop at the walls of the intermediate heat exchanger is determined as 50 K. So the inlet and outlet temperatures of sodium in the intermediate heat exchanger are 573 K and 773 K, respectively.

The steam cycle is configured with a reheat. The initial steam temperature and the reheat temperature are equal to 743 K. The initial steam pressure is taken as 18 MPa. The reheat pressure is optimized as 3 MPa. The steam turbine has eight regenerative take-offs. The pressure in the condenser is 9 kPa.

The minimum temperature drop of 40 K of the steam generator heating walls is realized at the outlet because of the isothermal segment of vaporization in the temperature-enthalpy diagram. The temperature of the feeding water is computed as 450 K. The efficiency of the steam cycle equals 0.417. Taking into account the target gain of 100, the blanket multiplication of 1.15, the fusion power of 1000 MW, and the driver efficiency of 0.25, one comes to the net efficiency of the plant as 0.373 and the net power per one reactor as 407 MW.

5. CONCLUSIONS

The concept of a power plant for fast ignition HIF involves a number of net components and devices. The high power heavy ion driver and the cylindrical target seem to have a clear basic design. The massive target causes some redistribution of energy fluxes resulting from the microexplosion. Altogether the long driver train and target axis stabilization in flight are matters of concern.

The reactor chamber with its wetted first wall has a minimum number of ports for beam injection. The composition of the reactor chamber in two sections makes the condensation problem easier and partly lessens pressure loading. The problems of coolant droplets and thermal stresses in blanket materials are of major concern in the reactor chamber.

The energy conversion system consisting of three loops is a convenient object for the plant efficiency optimization and thermal equipment development.

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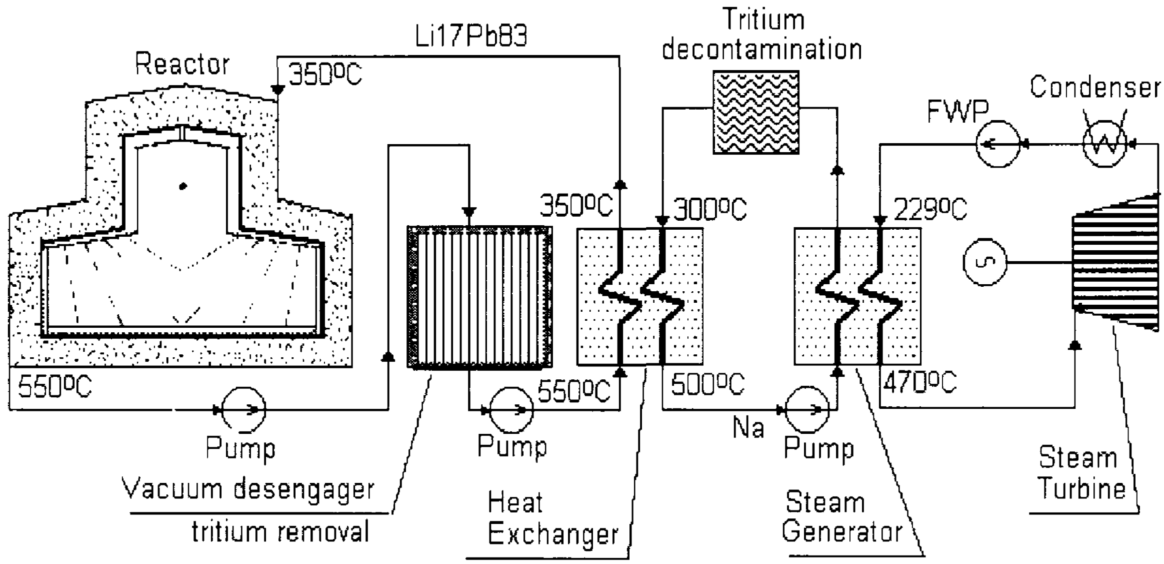

Fig. 4. Thermal scheme for FIHIF power plant.

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