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Neutronic investigations of a laser fusion driven lithium cooled thorium breeder

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A B S T R A C T

The paper investigates the main parameters of a Laser Inertial Confinement Fusion Fission Energy (LIFE) driven thorium breeder. A similar blanket to the (LIFE) engine design in Lawrence Livermore National Laboratory is chosen in order to allow mutual feedback between two geographically separated teams towards a more advanced and improved design under consideration of totally independent views. In the basic design, frozen (D,T) fusion fuel ice is shot to the center of 5 m diameter spherical fusion reactor chamber cavity in pulsed mode (10–30 Hz). Fusion fuel burns through direct or indirect laser beam irradiation. The first wall surrounds the fusion chamber and is made of S-304 steel (2 cm). The fusion reactor cavity is kept in high vacuum. It is followed by a natural lithium coolant zone. A 2nd S-304 layer (2 cm) separates the lithium zone on the right side from the graphite reflector (30 cm). The outer boundary of the graphite reflector is also covered with a 3rd S-304 layer (2 cm).

The calculations have been performed for a fusion driver power of 500 MW_{th} with the last available version of MCNP, namely with MCNPX-2.7.0. In the first calculation phase, the thickness of the natural lithium coolant-tritium breeder zone (ΔR_{Li}) has been varied as 50, 60, 70, 80, 90 and 100 cm to select the coolant thickness ΔR_{Li} to have a satisfactory tritium breeding ratio (TBR) for continuous fusion reactor operation. For a pure fusion blanket without any fissionable elements in the coolant, TBR values are calculated as 1.237, 1.312, 1.370, 1.415, 1.449 and 1.476, respectively, for corresponding coolant thicknesses. A ΔR_{Li} value of 50 cm would keep TBR > 1.05 for self-sustaining tritium supply. These ΔR_{Li} values lead to blanket energy multiplication values of $M = 1.209$, 1.216, 1.219, 1.222, 1.223 and 1.224, respectively, and have been calculated, as a result of exoenergetic neutron absorption in ^{6}Li. For coolant thickness values >50 cm, the increase of "M" would remain minor.

In the second phase, ThO_2 has been suspended in the form of micro-size tristructural-isotropic (TRISO) particles in the lithium coolant for ^{233}U breeding. TRISO fuel has the great advantage of high mechanical stability. Furthermore, fission products will be separated from the coolant. TRISO particles have been dispersed homogenously in the lithium coolant with volume fractions $V_{tr} = 1$, 2, 3, 4, 5 and 10 vol-%. Calculations with $\Delta R_{Li} = 50$ cm and by variable V_{tr} result with TBR = 1.229, 1.222, 1.214, 1.206, 1.1997 and 1.1622, respectively. Parasitic neutron absorption in Thorium decreases the TBR values. For $V_{tr} < 5$ vol-% TRISO in the coolant, the increase of the neutron absorption in thorium will be compensated to a great degree through neutron multiplications via ^{232}Th(n,f) and ^{232}Th(n,2n) reactions so that the sacrifice on TBR remains acceptable. However, for $V_{tr} > 5$ TRISO vol-%, neutron absorption in thorium reduces TBR drastically. On the other hand, the blanket energy multiplication M increases with thorium volume fraction, namely as $M = 1.2206$, 1.2322, 1.2426, 1.2536, 1.2636, 1.3112 for respective TRISO volume fractions due to the contribution of fission energy. Fissile fuel productions in the blanket are calculated as 17.23, 33.09, 48.66, 64.21, 79.77 and 159.71 ^{233}U (kg/year), respectively.

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1. Introduction

1.1. National Ignition Facility (NIF)

The growing world population and the significant increase in the population aspiring to a better standard of living results in higher energy consumption levels and thus increases world energy needs. Commercial fusion power could potentially fill the gap between supply and demand by providing an affordable, virtually limitless source of energy. Research teams worldwide have been working on this challenge for decades. Fusion energy for the purpose of industrial power production in the multi megawatt range is being pursued on two mainline projects with international collaboration ① on the International Tokamak Experimental Reactor (*ITER)* for magnetic fusion energy (MFE) and ② on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) for inertial fusion energy (IFE) (Damkroger, 2010). The latter is designed to produce fusion energy in the 40–50 MW_{th} range through indirect-drive, inertial-confinement fusion with simultaneous operation of all 192 laser beams in a spherical chamber of 10 m diameter. NIF's 192 beams are focused through a hole in the top and bottom of a gas-filled, gold hohlraum, a centimeter-size enclosure that traps radiation. In the center of the hohlraum is a 2-millimeter-diameter pellet filled with fusion nuclear fuel in both gas and solid forms, shown in Fig. 1 (Damkroger, 2010; Powers et al., 1995). During a shot, NIF laser light enters the two laser entrance holes to form an inner cone that illuminates the hohlraum wall near the equator of the capsule and laser beams strike the internal walls of the cryogenically cooled hohlraum and are converted to X-rays that irradiate and heat the outer layer of the fuel pellet, see Fig. 2 (Lindl, 2013). As this layer expands and ablates, it rapidly compresses the pellet's core, driving it to temperatures and pressures greater than those in the interior of the Sun. These extreme conditions cause the fuel's nuclei to fuse and release far more energy than that needed to initiate the reaction (Powers et al., 1995). Progress on NIF became a guideline for design studies on a Laser Inertial Confinement Fusion-Fission Energy (LIFE) for LLNL scientists.

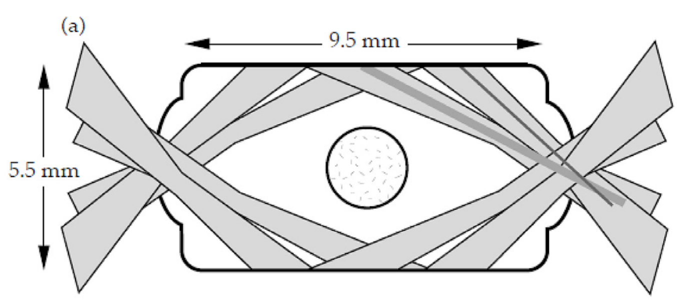
1.2. Potential of fusion-fission (hybrid) reactors

Market penetration of pure fusion power reactors with high energy gain value (*Q*) will require substantial research and development efforts, before fusion electricity can be counted as a new component in energy sector. However, a fusion-fission (hybrid) reactor could combine the advantages of both fusion and fission. It could bring commercial fusion electricity production to an earlier time than pure fusion reactors.

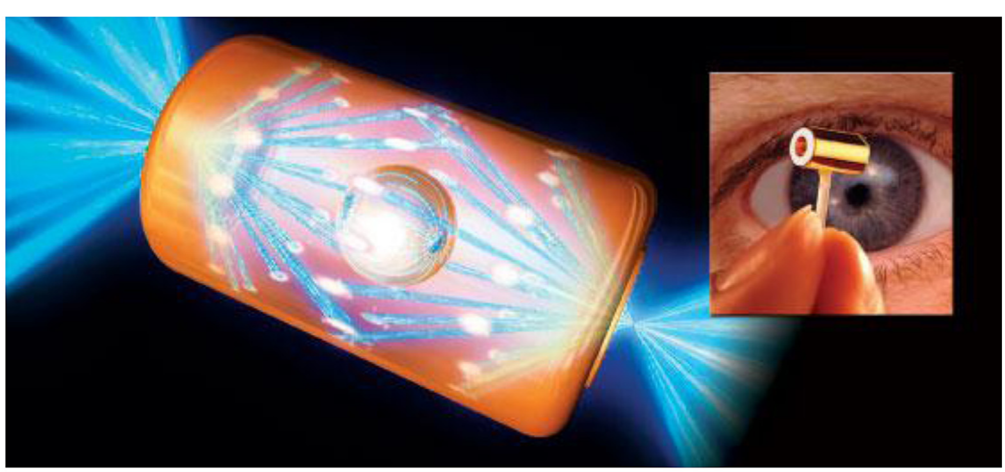
The main fusion reaction (*D*,*T*) produces abundant high energetic neutrons:

$$D + T \rightarrow \alpha(3.5\text{ MeV}) + n(14.1\text{ MeV}) \quad (1)$$

Fusion neutron energy is significantly higher than the threshold fission energy of ^{232}Th and ^{238}U. Hence, these passive isotopes become fissile fuel through 14-MeV fusion neutron irradiation.



(a)



(b)

Fig. 1. NIF target design (a) Target and illumination geometry for baseline NIF target design (Powers et al., 1995). (b) An artistic view (Damkroger, 2010).