A Nonvaporizing First Wall for Inertial-Confinement-Fusion Reactors

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ABSTRACT

We present a new concept for a stationary inertial-confinement-fusion reactor. The concept uses a sacrificial x-ray and debris shield around each fuel pellet that extends the energy deposition time in the first wall from <10 ns to ~100 μs. This permits the design of a first wall surface that does not vaporize.

1 INTRODUCTION

In a conceptual design for an inertial-confinement-fusion reactor used to generate electrical power, roughly two-thirds of the energy released from the deuterium-tritium fuel pellets is in the form of 14-MeV neutrons. The remaining one-third of the energy is in the form of soft x rays and ion debris. Some of the neutron energy and all of the x-ray and debris energy is deposited in the first wall surrounding the fuel pellets. The energy from the neutrons is dispersed deeply enough that the first wall temperature rises only a few degrees. However, the energy from the x-rays and ion debris is deposited so superficially and so quickly (<10 μm deep within <10 ns) that the surface of the first wall vaporizes unless placed at an uneconomically large radius.

Previous solutions to the vaporization problem have included first walls made of flowing liquid lithium (Blink et al., 1985) or flowing lithium-bearing granules (Pitts, 1986). (Fusion reactors using deuterium-tritium fuel require lithium because it breeds tritium to replace that burned in the fusion reactions.) In these solutions, the surface of the first wall does vaporize as soft x-ray and debris energy is absorbed, but the wall is continually renewed. We discuss here a new approach (Fig. 1) in which a sacrificial x-ray and debris shield is placed around each fuel pellet as it is injected into a spherically shaped, 5-m-radius reactor. The shield itself vaporizes, but in the process it converts the x-ray and debris energy into kinetic energy and spreads out the time during which this energy is deposited at the surface of the first wall by over four orders of magnitude. Energy can now be conducted into the first wall fast enough to keep the surface temperature below the vaporization point.

In our concept, the reactor operates at 5 Hz with 300-MJ-yield fuel pellets. A 3- to 5-MJ laser or ion-beam driver is used to compress each fuel pellet to fusion conditions. A vacuum is required inside the reactor for good driver-beam propagation. Helium gas at 5-MPa pressure cools the first wall and also a 1-m-thick blanket of $LiAlO_2$ granules that surrounds the first wall. The helium flows directly to a closed-loop, helium-gas-turbine, power-conversion system which produces the electrical power. The peak operating temperature of

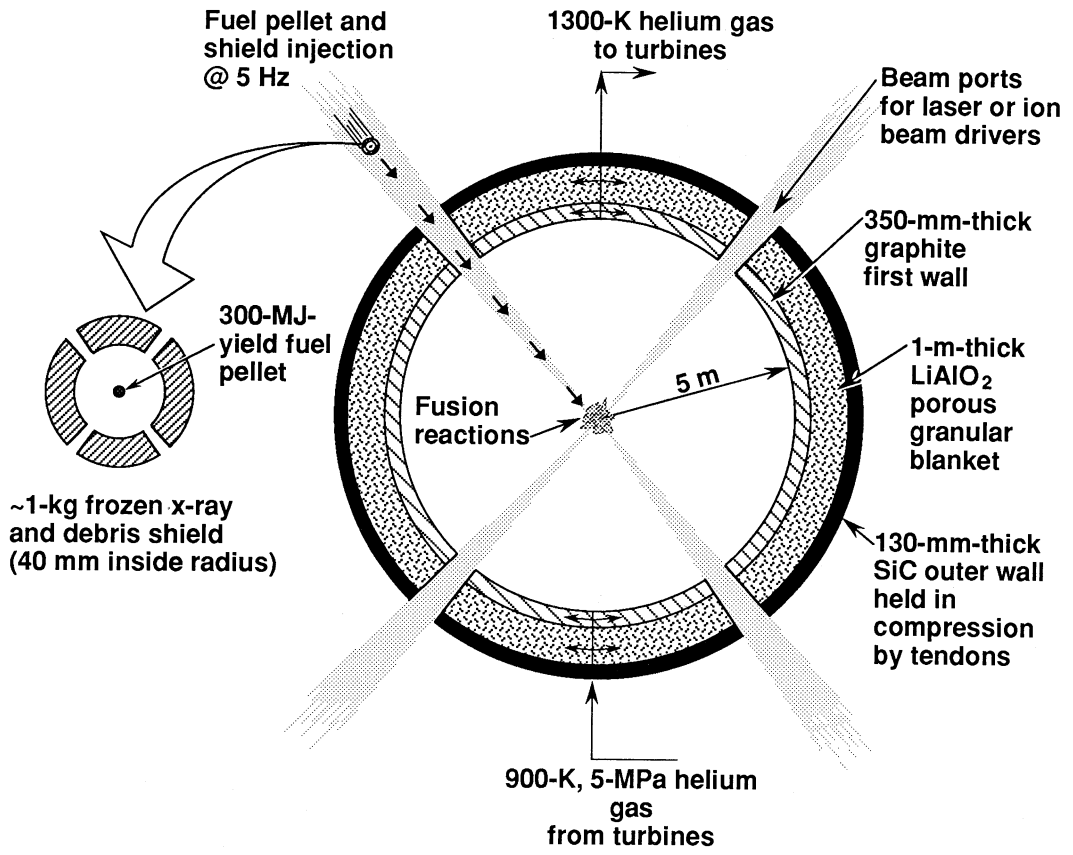

Fig. 1. Schematic of a simple, stationary, dry-wall reactor concept. An ~1-kg sacrificial x-ray and debris shield is injected along with each fuel pellet at 5 Hz. Holes in the shield line up with the beam ports.

the helium is 1300 K, which results in a net plant efficiency of ~50%. There is no intermediate loop. We use a 350-mm-thick first wall of graphite in our initial design. Graphite has the advantages of being nontoxic and relatively inactive neutronically. Its atomic structure permits easy release of helium generated when neutrons are absorbed in the wall, mainly by $^{12}C(n,n')3\alpha$ reactions. A disadvantage is that a thick graphite wall absorbs about one-third of the neutrons so that the tritium breeding ratio is ~0.7--less than the required value of unity. This means that tritium would need to be transported to the reactor site to replace about one-third of the tritium that is burned in the fusion reactions. Therefore, we are also considering BeO, $LiAlO_2$, and Li_2O as first wall materials. Elimination of the carbon wall increases the tritium breeding ratio. Also, BeO is a neutron multiplier and if used produces a tritium breeding ratio of ~1.2.

A nonvaporizing first wall has many advantages for power reactors. The wall lifetime is extended because there is no erosion. This reduces both waste and cost. Shock waves strong enough to fracture or spall material below the surface if there is vaporization are reduced to acceptable magnitudes. Unlike earlier designs featuring rotating fusion chambers, this reactor is stationary. This not only simplifies the design and reduces cost, but it also allows the driver-beam ports to be located so as to optimize illumination of the fuel pellets.

The shield can be made from a number of materials and have a variety of sizes. Because the fuel pellets will probably be cryogenic, we previously selected

frozen nitrogen as the shield material in a 1400-MJ-yield, 3-m-inner-radius aluminum target chamber for a proposed laser-fusion research facility (Pitts, Woodworth, and Tabak, 1988). Nitrogen has a number of desirable features. It will not condense on room-temperature optical or diagnostic surfaces, and it is chemically benign. Its thermal inertia protects the fuel pellet from higher temperature surroundings when cooled to temperatures at or below that of the fuel pellet. Even if the shield is kept near its melting point (~60 K), it still thermally isolates the fuel pellet from the ~1700-K first wall. Another advantage is that nitrogen dissociates as the shield absorbs x-ray and debris energy from the fuel pellet, expending 34 MJ/kg in the process. This keeps temperatures in the shield low, which reduces the rate at which energy can be radiated to the first wall. Yet, nitrogen requires only 330 kJ/kg to vaporize. Hence, solid nitrogen shrapnel, which could damage critical components, most likely would not be generated even if the fuel pellet produced zero yield. Just the driver used to illuminate the fuel pellets produces over 10 times the energy required for vaporization. Gaseous nitrogen, produced when the shield is vaporized, can be vacuum pumped out through the driver-beam ports.

We are also considering shields made from either water ice or dry ice (frozen H_2O or CO_2), which remain gaseous following each fusion pulse and which are less expensive to manufacture. These materials would have a higher initial temperature (190 and 270 K) than nitrogen and would produce a larger, but acceptable, heat load on the fuel pellet. They also dissociate, producing free oxygen that could react with surrounding materials. Furthermore, tritium separation is more difficult if H_2O is used. Shields made of materials that condense at temperatures higher than the first wall surface (e.g., graphite) may also be used. The shield material would then condense on the first wall surface, producing a protective coating. Excess condensed material can be removed on a steady basis through the same ports used for the vacuum system and the bottom.

2 X-RAY AND DEBRIS SHIELD DESIGN

We used the LASNEX computer code (see Zimmerman and Kruer, 1975) to calculate the response of the shield to a fusion pulse and its interaction with the first wall. LASNEX is optimized for high-temperature plasmas but has been verified at low temperature by comparing the equation of state used in LASNEX with experimental material properties and with physical arguments or sensitivity studies. Our calculations assume an imploded fuel pellet and an x-ray and debris shield. The fuel pellet ignites and burns; its yield energy is transported to the surrounding material, and the material response is determined. We used a combination of an empirical equation of state for ions and a Thomas-Fermi equation of state for electrons. The result contains corrections for chemical bonding and includes both sensible and latent heat as well as ionization. Dissociation is approximated, when appropriate, using a temperature-dependent pressure multiplier. We assume local thermodynamic equilibrium.

We designed three different shields, one each of carbon, water ice, and frozen nitrogen. Each shield is massive enough (between 880 and 1000 g) to absorb all the x-ray and debris energy and a fraction of the neutron energy. The inner part of the shield is supersonically heated to temperatures high enough to radiate rapidly, but very quickly the radiation wave stalls as more and more mass is encompassed in the radiation wave. The bulk of the absorbed energy is then transported by shock propagation and neutron transport inside the shield. The shield material vaporizes as the shock wave moves outward, but there is little radiation from the outer shield surface. Various portions of the shield material are accelerated toward the first wall at different speeds and arrive at the first wall over a time span of ~10 μs--giving up about 10% of their energy to the wall before rebounding. Multiple reflections follow, and the total energy deposition time in the first wall exceeds 100 μs, which is four

orders of magnitude larger than the <10-ns initial energy deposition time in the shield.

Because the shield material expands as it travels outward, it is cool when it reaches the first wall. However, its temperature increases rapidly as it stagnates against the wall and rebounds. At this point, radiation is the dominant mechanism for energy transfer to the wall. Shields made of nitrogen, water ice, and dry ice dissociate; this process absorbs energy and keeps the peak radiation temperatures low enough that the flux of energy can be conducted into the wall without causing vaporization. Carbon, on the other hand, has a large heat of sublimation (~60 MJ/kg) without dissociation, which also keeps radiation temperatures low. Time spans of interest (<1 ms) do not permit the development of convection cells, and conduction through the gas is small. Figure 2 plots the transient rise in temperature at the surface of a 5-m-radius graphite first wall as it is hit by the stagnating gas, for three shields. We calculated these values, using the TOPAZ finite-element conduction-heat-transfer code (see Shapiro, 1986), with input energy fluxes determined using LASNEX. The carbon and nitrogen shields result in the largest temperature rises, which means that the surface temperature of the wall just before a fusion pulse must be lower than for a water-ice shield. Otherwise, the maximum allowable wall surface temperature will be exceeded. However, the temperature rise for any shield can be reduced by increasing the shield mass. A low initial wall temperature is undesirable because it reduces the temperature of the helium gas (the medium for transferring energy to the power conversion system) and hence the overall efficiency of the power plant. Optimization remains to be completed.

3 REACTOR DESIGN

We discuss here the design of the reactor in Fig. 1 that has a 350-mm-thick graphite first wall and a 1-m-thick, 50%-dense $LiAlO_2$ granule blanket. We first established the first wall inside radius, knowing that the peak surface temperature should not exceed 2400 K and that a reasonable power conversion system operates with turbine entrance and reactor entrance temperatures of 1300

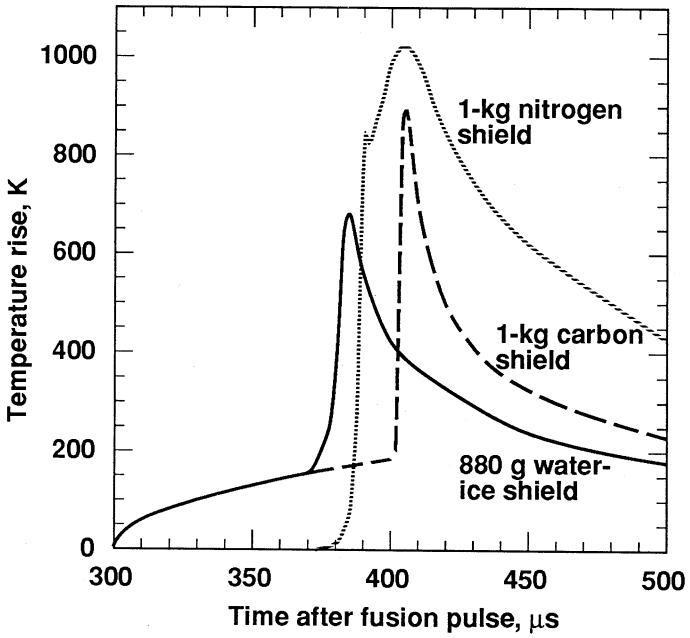

Fig. 2. Temperature rise at the surface of a carbon first wall for three different x-ray and debris shields.

and 900 K, respectively (Maya, Schultz, and Project Staff, 1985). For a given wall radius, we subtracted the surface temperature rise of Fig. 2 from 2400 K to obtain the initial surface temperature before each fusion pulse. We then subtracted the temperature difference necessary to conduct heat from the wall surface to the cooling channels located 10 mm below the surface and the film drop across the boundary layer of the helium gas flowing inside the cooling channels. The result is the bulk helium temperature. All of these temperature differences decrease with the square of the wall radius because the area for heat transfer increases. We selected the first wall radius that produced a bulk helium temperature of 1060 K for the following reason: We knew that about one-third of the yield energy would need to be conducted from the surface to the cooling channels and that some neutron heating would occur inside the wall. We estimated that ~40% of the yield energy in all would be added to the helium gas within the graphite wall. We approximated the helium as a perfect gas so that its temperature rise in the graphite wall would be 40% of the temperature difference between the reactor entrance and the turbine entrance. The result is a bulk helium temperature leaving the first wall of 1060 K. The remaining 60% of the yield energy would be added to the helium in the $LiAlO_2$ blanket, bringing the helium temperature leaving the reactor and entering the turbines to 1300 K. The 5-m-radius first wall in Fig. 1 corresponds with the use of a 880-g water-ice shield. If a 1-kg carbon shield were used, we would need a 5.5-m-radius first wall in order to obtain the desired 1060-K bulk helium temperature.

Next we determined that a first wall thickness of 350 mm was necessary to withstand buckling by using

$$(1) \qquad P' = 0.365Et^2/r^2,$$

where P' is the pressure of the helium gas in the blanket multiplied by a safety factor of four, E is Young's modulus equal to 11 GPa, t is the wall thickness, and r is the wall radius equal to 5 m (Roark, 1965). Peak compressive stress is 40 MPa, which offers no additional constraint because it is over four times less than the expected compressive strength of 190 MPa. Using LASNEX, we calculated that the peak shock pressure produced in the wall by the shield impact is only 8 MPa. Wall hoop stress produced by the shield impact is insignificant.

The lifetime of the first wall is affected by cyclic stress variation caused by thermal transients and impact of the shield. However, the high-pressure helium gas present on the outside keeps the wall in compression, and stress variations described above change only the magnitude of compressive stress. Tension stresses never occur. Materials are difficult to fracture under compression conditions as long as the compressive strength is not exceeded. Our peak compressive stress reaches 115 MPa (75 MPa thermal plus 40 MPa compressive), which is only 60% of the 190-MPa compressive strength of graphite. Strength properties can decrease because of radiation damage due to 14-MeV fusion neutrons, but the actual magnitude is unknown. Experimental determination will most likely be needed to establish a quantitative value. Hence, first wall lifetime is an issue to be evaluated with this reactor concept.

The outer wall in Fig. 1 is made of silicon carbide held in compression by tendons--a design similar to that used in Cascade (Pitts, 1986). A thickness of 130 mm is required to contain the high pressure helium gas present in the blanket region. The outer wall is protected from neutrons by the blanket material so radiation damage is not an issue here.

Our reactor concept is new, and variations of the design are under consideration. We are presently studying: (1) different combinations of shield and wall materials, and their dimensions; (2) different blanket materials; (3) the use of a steam Rankine power-conversion system in conjunction with a

metal wall; and (4) optimization to obtain minimum cost and minimum activation with inherent safety.

4 CONCLUSIONS

We present a new reactor concept that uses an x-ray and debris shield around each fusion fuel pellet as it is injected into the reactor. This permits the design of a nonvaporizing first wall. The concept has a number of important advantages that could have far-reaching implications: the reactor is stationary, which simplifies the design over other concepts and has the potential for lowering costs; there is no first wall erosion, which extends the wall lifetime and reduces waste; and driver beam ports can be placed at optimum positions for illumination of fuel pellets.

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