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ELECTRIC POWER FROM LASER FUSION: THE HYLIFE CONCEPT*

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ABSTRACT

A high yield lithium injection fusion energy chamber is described which can conceptually be operated with pulsed yields of several thousand megajoules a few times a second, using less than one percent of the gross thermal power to circulate the lithium. Because a one meter thick blanket of lithium protects the structure, no first wall replacement is envisioned for the life of the power plant. The induced radioactivity is reduced by an order of magnitude over solid blanket concepts. The design calls for the use of common ferritic steels and a power density approaching that of a LWR, promising shortened development times over other fusion concepts and reactor vessel costs comparable to a LMFBR.

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The production of base load electricity in an economically competitive and environmentally acceptable manner is a major goal of fusion research and development. Should the progress of the Inertially Confined Fusion (ICF) physics program continue at the current rate, we will have demonstrated the scientific feasibility of ICF in the early to mid 1980's. The major effort will then shift to a technology development program in which the components and subsystems required in a commercial power plant will be designed, built, tested and integrated into working prototypes. The three major systems of an ICF power plant to be developed are:

1. A high average power driver, such as a laser or ion beam, with the required efficiency ($\geq$ 1%), pulse repetition rate ($\geq$ 1 Hz), and reliability ($\geq$ 70%).
2. A manufacturing facility capable of producing DT pellets at the required rate, with the requisite tolerances on layer thickness and surface finish.
3. An energy conversion chamber required to absorb a repetitively pulsed flux of neutrons, x-rays and debris and convert the pulsed energy to steady thermal power.

This paper is limited to a discussion of the energy conversion system, which itself requires the development of several elements:

a. A first-surface able to withstand the effects of x-rays, debris and neutrons,
b. structural materials able to withstand the cumulative damage effects of neutrons and cyclical thermal and dynamic stresses,
c. a repetitively pulsed target injection and beam focusing system, with elements lasting sufficiently long to not compromise the availability of the power plant, and
d. a tritium breeding and recovery system.

Over the past few years scoping studies and preliminary conceptual design efforts have been carried out at Lawrence Livermore Laboratory to identify the reactor concept of greatest promise in addressing these issues.[1-4] Our guiding philosophy is very important, for it differs from that of other reactor design groups in magnetic and laser fusion.

First, we emphasize the characteristics of advanced fusion pellets[5] in determining reactor design, e.g., through the size of yield, energy spectra of the output, required irradiation requirements, etc. Second, instead of looking toward the development of exotic materials to withstand the expected radiation environment, we seek to modify the radiation flux and spectra in order to use ordinary reactor materials and techniques currently within the fission state-of-the-art. With this strategy we expect to fully capitalize on the unique simplicity of inertially confined fusion and dramatically shorten the period of technology and materials development required to bridge the gap between scientific feasibility and commercialization.

In October, 1977, we began a laser fusion power plant conceptual design study based on an attractive fluid wall reactor concept. Approximately 16 man-years of effort are being invested in this study[6] which is now heading toward completion, with outside contractors such as Rockwell International, the Energy Technology Engineering Center, Bechtel National, the University of California at Davis, and the Colorado School of Mines contributing expertise.

We call our fluid wall reactor concept the HYLIFE converter; the acronym stands for High Yield Lithium Injection Fusion Energy converter. This reactor concept constructively addresses the problems of pulsed energy release while maintaining all the positive features of the previous lithium waterfall reactor concept.

In this paper, we describe the HYLIFE converter as it has evolved, and evaluate it in the context of a power plant with laser and target parameters which are representative of our current understanding of the technology.

The target performance postulated for this design study has been based on designs developed by the target design group at LLL.[6] These fusion targets have features which significantly affect power plant design. Energy gains approaching 1000 are predicted when they are irradiated with 1 to 4 MJ of short wavelength laser light ($\lambda < 2$ μm). With target gains between 200 and 1000, the laser system efficiency can be relaxed to 1 to 5%. Thus, the KrF*/CH backward wave Raman pulse compressor with a wavelength of 0.268 m and a projected efficiency of 2 to 4% would be an excellent driver for these high gain targets. We are also evaluating the mating of a heavy ion accelerater to the HYLIFE converter.

The high target gains and high laser input energies result in high energy yields per pulse (200 MJ $<$ Y $<$ 4000 MJ). High gain targets also exhibit relaxed requirements for uniform target illumination and target surface finish tolerances. By relaxing the uniform illumination requirements, we can consider two sided target irradiation with longer focal length optics (f/10 to f/100). At focal lengths of 10 m, the final optics would survive the microexplosion but might have to be replaced at relatively short intervals. At focal lengths of 100 m, the damaging effects are reduced by two orders of magnitude, thus assuring the survival of the final focusing elements for sufficiently long intervals to not adversely affect the plant capacity factor. The relaxation in target surface finish requirements also translates into a reduction in target fabrication costs.

INTERACTION OF THE FUSION MICROEXPLOSION WITH LITHIUM IN THE CAVITY

The D-T fusion reactions in the compressed target ($\rho R \approx 3$ gm/cm^2) release about 80% of their energy as 14.1 MeV neutrons with the remainder being 3.5 MeV alphas. However, the alpha particles are absorbed and some of the 14.1 MeV neutrons are attenuated in the compressed target. Of the total fusion energy produced approximately 68% escapes as slightly degraded neutrons and the remaining 32% as x-rays plus energetic target debris. The x-rays include a hard component generated from the hot burning pellet and a cool component radiated from cooling debris as it expands.

Radiation transport and hydrodynamic calculations have been made to determine the deposition of microexplosion energy in the fall and the response of the fall to this energy. In these calculations a one meter thick curtain of lithium is initially placed 2.5 m from the microexplosion with the first structural wall located at 4 m. The calculations have been performed in both spherical and cylindrical geometry. The results from the calculations are described qualitatively below and more details are presented in Refs. 7 and 8.

The debris and soft component of the x-ray energy is deposited in a very thin region of the fall. The hard component of the x-ray energy is deposited deep in the fall. More than 95% of the fusion neutron energy is deposited in the one meter lithium region where it is multiplied by about 25% via the exoergic process of neutron capture in ^{6}Li. Although the energy deposited in the fall by each microexplosion is only enough to raise the mixed mean temperature by $\sim$ 15 degrees Celsius, the concentration of energy deposition in space (soft x-rays, debris) and time (neutrons and hard x-rays) results in violent disassembly of the fall. The liquid strikes the structural wall causing an inertial loading. The transient stress caused by this liquid-wall impact determines the design basis for the first wall. Three distinct effects contribute to the fall disassembly. The deposition of the soft x-rays and debris in a thin inner layer ($\sim$ 8 ns) causes a shock wave to propagate through the layer. When this shock reflects, it spalls off an outer layer of liquid at relatively high velocity. About 50 μs later, as the blowoff vapor accumulates in the central high pressure region it exerts a significant outward force on the curtain, accelerating it outward as an intact annular slug. The neutron energy is deposited throughout the fall in a few μs. The resulting sudden temperature and pressure rise in the fall produces expansion waves that move inward from both surfaces of the fall. The hot vapor in the reactor center pushing outwards on the curtain will reverse the inward moving lithium, accelerate it outwards where it impacts the wall. Hydrodynamic calculations for the response of a single annular curtain of lithium represent the worst case, for the expected stress is the largest. The fluid configuration we anticipate using should cause significantly reduced stresses in the reactor structure than the single annular curtain, but it is far more difficult to calculate accurately.

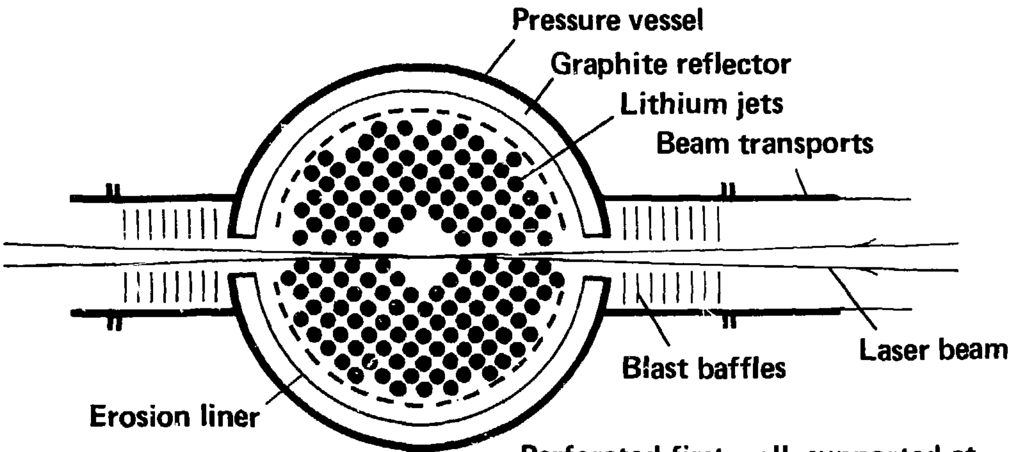
DESCRIPTION OF THE HYLIFE CONVERTER REACTOR

In line with our philosophy of using only existing materials, we are only considering stainless or low alloy ferritic steels for the primary structural materials. Comparative analyses that consider lithium corrosion[9] and resistance to radiation damage[10] currently favor ferritic steels.

A cross-section of the HYLIFE chamber is shown in Fig. 1, corresponding to a horizontal slice through the target plane. It features several concentric annular regions: 1) A thick outer pressure vessel which is primarily in steady compression due to the average inside pressure of less than 0.1 torr, 2) a graphite reflector to deal with the 5% of the energy and 35% of the neutrons which initially escape the lithium blanket, 3) an erosion shield which covers the graphite and takes the liquid lithium impact - this shield does not support the weight of other components, 4) an empty volume of 30-50 cm thickness which provides surge protection when there is transient fluid (liquid or gas) pressure on the first wall, 5) a perforated inner first wall, the primary purpose of which is to withstand the fluid impact loads on the erosion shield - it is supported only at the top and bottom and is primarily designed to take the transient tensile hoop stress, 6) the inner liquid lithium blanket region.

The fluid configuration currently favored is a close packed array of 400 cylindrical jets, 10-30 cm in diameter, arranged in a hexagonal close packed pattern. This configuration removes the defect of the annular curtain geometry, i.e., the impact stress resulting from the impact of the fluid accelerated by the inner high pressure blowoff gas. In the

TOP VIEW OF HYLIFE CHAMBER: CROSS SECTION THROUGH TARGET PLANE



Perforated first wall, supported at top and bottom and allowed to take transient stress in pure tension

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Figure 1

HYLIFE geometry this hot gas merely blows through the array of jets, like wind through trees. The force of the expansion from neutron induced motion is primarily taken up in liquid-liquid impact of colliding jets.

The injection velocities of 4 m/sec will allow the jets to reestablish before the next microexplosion at the selected repetition rate of 1.1 Hz. Jet stability analyses presented by Kang[11] indicate that 30 cm jets with inlet velocities of 4 m/sec exhibit intact lengths which are longer than 20 m. This intact length is larger than the 7 meters that is required to insure the jets will not break up in the chamber. The area fraction occupied by liquid lithium is about 30% at the midplane, perhaps 80% at the top. We want to minimize the empty space and lithium flow rate while providing the $\sim$ 100 cm of lithium required to absorb the fusion energy and minimize neutron damage to the structure. The lithium jet diameter must be small enough so that a reasonably uniform average lithium thickness is provided; the jets must be large and "stiff" enough so that the gas from the x-ray absorption blowoff does not immediately push all the jets together to form a continuous sheet of fluid.

The array of jets can easily be arranged so that there are only two lines of sight "through the dense forest"; the target and laser beams are injected horizontally between the lithium jets in these places.

A conceptual view of the HYLIFE chamber is shown in Fig. 2. The pressure vessel consists of a cylindrical body, a hemispherical top with six or eight lithium inlet pipes and a surge tank 'cap', and a bottom piece with a large cylindrical downcomer. The first wall assembly, which is a perforated basket supported at the top and bottom, sits inside the pressure vessel. Figure 2 also shows the injector plate or nozzle manifold which establishes the array of jets. The injector plate separates the high pressure plenum from the low pressure side of the chamber and is sandwiched between the top and main sections of the pressure vessel before bolting.

FEATURES OF THE HYLIFE CHAMBER

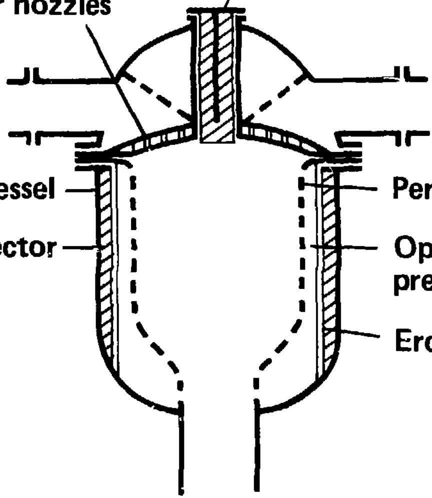

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Figure 2

The lithium flow pattern is illustrated in Fig. 3. The lithium flows into the upper plenum from a half dozen or so inlet pipes and then is forced through the injector plate. Because the fusion pulse can cause significant transient overpressures (and possibly backflow), a surge tank is provided on the very top. The jets are formed in the chamber, and the basket is designed to accumulate some fluid although it continually pours out toward the downcomer region. This prevents shock waves from propagating directly through a pool of liquid to the structure. This is an essential feature which solves a problem endemic to all our previous fluid wall concepts.

Note that the side view presented in Fig. 3 is in a direction along the laser beam axis. The beams project through a narrow (∿ 30 cm) separation between rows of crossing jets. Figure 4 shows the beam entrance more closely from another view. The pellet and the laser beams are injected from the sides. Underneath the laser beams, the slot is fully protected by streams of lithium injected in an arcing fashion to protect all the metal surfaces behind it. Finally, Fig. 5 shows a three dimensional view of this simple geometry.

PERFORMANCE PARAMETERS OF THE HYLIFE CONVERTER

Feasible laser and target parameters have been selected in order to evaluate the HYLIFE converter concept in the context of a laser fusion power plant. The selected parameters and the resulting performance are presented in Table 1 for both a single and double chamber version. Several factors will affect the choice between one and two chambers: 1) The cost of the laser per unit of power decreases with higher repetition rate. This factor favors one laser system serving two chambers. 2) The reactor building and plant piping will be less expensive for one chamber. 3) Higher plant capacity factors may be possible with two independent chambers. 4) The higher yield per pulse in the single chamber design relaxes target fabrication constraints but exposes the reactor to a more severe environment. These factors and the interplay between them are being quantified in the remainder of the design study.

FLOW PATTERN IN HYLIFE CHAMBER

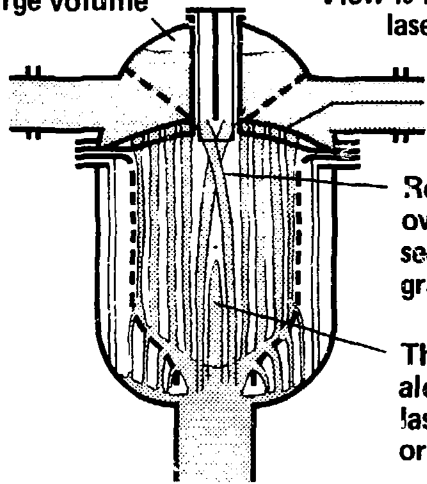

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Figure 3

SIDE VIEW OF HYLIFE CHAMBER IN PLANE OF LASER BEAMS

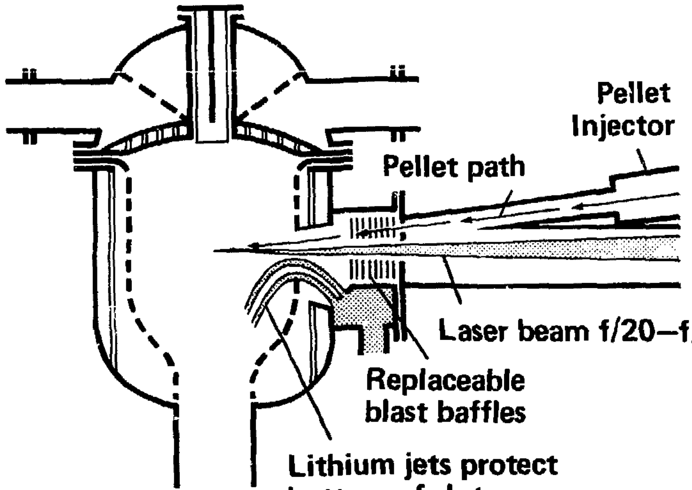

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Figure 4

HYLIFE CONVERTER CONCEPT

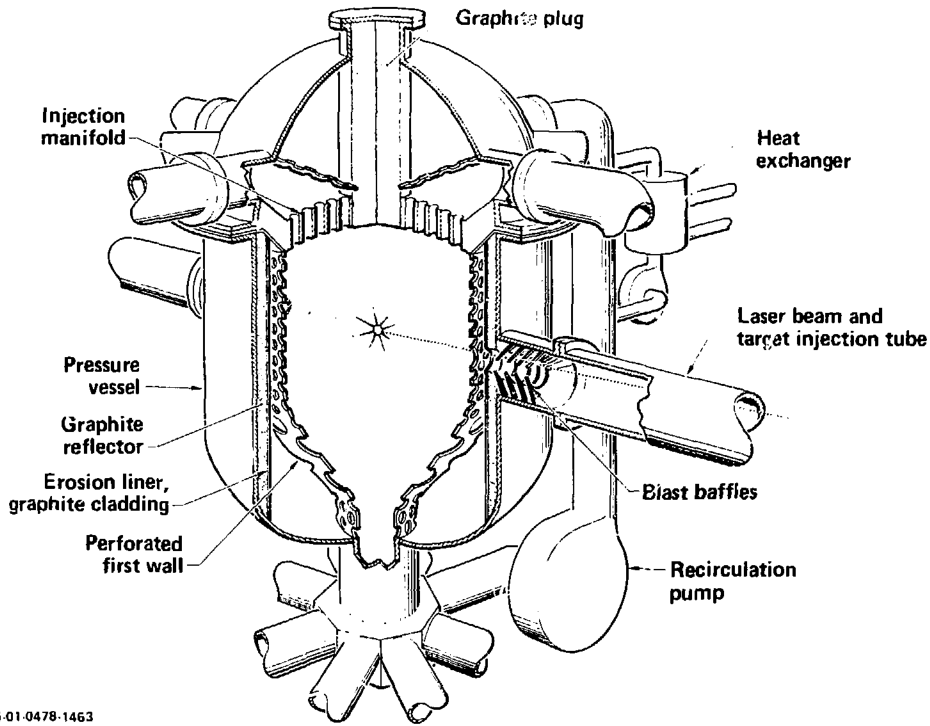

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Figure 5

LASER AND TARGET PARAMETERS FOR THE CONCEPTUAL DESIGN

	Feasible Range	Double Chamber Design	Single Chamber Design
Target gain, Q	100–1000	600	900
Laser efficiency (%)	1–5	3	3
Laser energy (MJ)	1–4	2	3
PRF per chamber (Hz)	1–3	1.5	1.1
Yield per chamber (MJ)	100–4000	1200	2700

POWER PLANT PERFORMANCE

	Double Chamber	Single Chamber
Fusion power (MW_T)	1800/3600	2970
Thermal power (MW_T)	2090/4180	3450
Gross electrical (η_T)	750/1500	1240
Laser input power (MW_E)	200	110
Chamber fluid circulation (MW_E)	20	16
Auxiliary power (MW_E)	120	110
Net electrical (MW_E)	1160	1005
System efficiency (%)	28	29

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Table 1

Neutronic calculations have been performed to determine several chamber parameters as a function of fall thickness. The parameters include system energy multiplications, power density, tritium breeding ratio, helium production and atomic displacement rates (dpa) in the structure. Helium production and dpa rates are used to estimate the damaging effects of 14 MeV neutrons in structural materials. Some of the neutronic results are summarized in Table 2 and more details are presented in Ref. 7.

Table 2 also gives the flow parameters for the HYLIFE converter based on single chamber design. In this design, fusion targets producing 2700 MJ of thermonuclear energy are irradiated by a 3 MJ laser at a rate of 1.1 pulses per second. The fusion energy is multiplied by a factor of 1.16 in the lithium filled chamber. This results in a power plant with a thermal power of 3450 MW. The thermal power is converted to electrical power at 36% efficiency. Of the total 1240 MW_e produced, 236 MW_e is circulated for power plant operation (lasers, lithium flow, and auxiliary power). It is interesting to note that less than 1% of the gross power (15 MW_e) is required to circulate the lithium through the chamber at the required flow of 120 m^3/sec.

Approximately 400-thirty cm diameter jets have been packed into a 3 m thick annular region with an inner radius of 0.5 m. The packing fraction of these jets at the reactor midplane is 0.35; thereby providing an equivalent 1 m of lithium between the target and first wall. Our neutronic analysis has shown that 1 m of lithium will attenuate the 14 MeV neutrons to a point where common stainless and ferritic steels are predicted to survive for more than 30 years. The lithium inlet velocity of 4 m/sec has been set by the requirement to have the lithium jets reestablish their flow between pulses which occur every 1.1 sec. The power density within the enclosed volume of the HYLIFE vessel is 5.6 W/cm^3. This can be put into perspective by comparing it to the power density enclosed within a boiling water reactor vessel which is 7.6 W/cm^3. Because we are using comparable materials at about the same power density as a present LWR, we do not expect the costs of our laser fusion reactor vessel to greatly exceed present fission reactor vessel costs.

HYLIFE CONVERTER PERFORMANCE

Flow parameters	
Outer radius of jet array	3.5 m
Inner radius of jet array	0.5 m
Jet diameter at inlet	0.3 m
Jet velocity at inlet	4.0 m/s
Jet packing fraction at inlet	0.8
Jet packing fraction at midplane	0.35
Equivalent lithium thickness at midplane	1.0 m
Lithium flow rate for jets	120 m^3/s
Pumping power for jets	11 MW
Blanket parameters	
System energy multiplication	1.16
Tritium breeding ratio	1.6
Neutron wall loading	15.4 MW/m^2
Power density within vessel	5.6 W/cm^3
Structure	Ferretic steel

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Table 2

ENVIRONMENTAL AND SAFETY ANALYSIS

Motivation for using advanced energy technologies stems primarily from the fact that they have inexhaustible fuel resources. All fusion reactor designs, both magnetic and inertial confinement, offer advantages in tapping the inexhaustible supply of deuterium present in seawater. Also, both systems produce less high level radioactive wastes than fission reactors and much less long-lived alpha emitting radioisotopes. Finally, fusion plants will be much smaller and utilize less land than solar central station plants.

The HYLIFE reactor concept incorporates the advantages in the social cost areas common to other fusion schemes while eliminating or reducing some of the problems inherent in the other systems. For example, the structural materials used are common steels which experience low activation rates because the lithium protection reduces fast neutron levels by a full order of magnitude. If low-alloy ferritic steels are used, the variety of parents for short-lived radioisotopes will be significantly reduced. In addition, remote handling facilities will be simpler and less numerous than for magnetic confinement reactors, which must replace liners or entire segments regularly. Finally, the HYLIFE reactor operates at power densities nearly as high as conventional boiling water fission power reactors, resulting in substantial resource savings in construction and equipment. The volume of low-level radioactive waste is also reduced by over an order of magnitude compared to other fusion designs because of the combination of high power density and 30-year structural life. Retention of these and other advantages of fusion power with concurrent reduction of disadvantages is the continuing goal of our design effort. Consideration of environment and safety issues at all stages of the design will facilitate this goal.

CONCLUSIONS

We have described the High Yield Lithium Injection Fusion Energy (HYLIFE) Converter. This concept has been shown to effectively cope with the problems associated with pulsed energy release and 14 MeV neutrons in inertial confinement fusion systems. Specifically, we have found that:

a) The HYLIFE converter can be operated with pulsed thermonuclear yields of several thousand megajoules and power densities approaching those of an LWR.
b) No replacement of the first-wall or blanket structure is required.
c) The power to circulate the lithium is less than 1% of the gross power.
d) The radioactive waste and biological hazard potential are reduced by more than 10 fold over concepts without fluid walls.
e) Common stainless or ferritic steels can be used for the reactor structure.

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