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Abstract

LIBRA-LiTE is a conceptual design for a 1300 MWe power plant using light ion inertial fusion. LIBRA-LiTE differs from the LIBRA design in its use of ballistically focused light ions to drive the target. Focusing magnets are positioned 2.05 m from the target, which, to mitigate neutron damage effects, has required a novel magnet design using liquid lithium as a conductor. A sacrificial film of liquid lithium protects the magnets, the target chamber side walls and bottom from the x-rays and debris released by the target microexplosion. The target neutrons deposit in a tritium breeding blanket of liquid lithium confined to woven metal tubes on the sides and in a pool on the bottom. The top of the target chamber is a metallic dome removed far enough (16 m) from the target to be a lifetime component.

Introduction

LIBRA-LiTE is a 1300 MWe power plant conceptual design using light ion beam driven inertial fusion. A schematic picture of the LIBRA-LiTE target chamber is shown in Fig. 1. LIBRA-LiTE differs from the LIBRA design [1] in the electrical power level, the ion transport system, and the target chamber design. The general parameters are shown for both designs in Table 1. Both designs use 127 TW/cm^2 of 30 MeV Li ions to drive the fusion target. Both designs use liquid metal first surface protection. The same liquid metal is used as breeding blanket material when confined in porous woven INPORT [2] units. LIBRA uses lithium-lead eutectic, LIBRA-LiTE, lithium. LIBRA uses plasma channels to propagate the ion beams, while LIBRA-LiTE uses ballistic propagation with focusing magnets near to the target. The LIBRA concept required insulation magnets to prevent breakdown between the channels and the chamber structures. Finally, the target chamber roof is fabric wetted with liquid metal in LIBRA, but is a dry dome in LIBRA-LiTE. The LIBRA-LiTE roof of the target chamber is a large dome that is far enough away from the target that it needs no liquid metal coating for protection from target x-rays and that neutron damage occurs slowly enough for the roof to be, along with the target chamber walls, a lifetime component. The target chamber and the 30 pulsed power driver modules fit in a single large building.

The choice of ballistic ion propagation in LIBRA-LiTE dictates some important features of the target chamber design. Ballistic propagation requires focusing magnets, each with a surface that faces and is near to the target microexplosion. Ballistic propagation also dictates that the gas in the target chamber at the time of beam propagation be high enough to insure current and charge neutralization but low enough to not excessively scatter the beam. To maximize the lifetime of the focusing magnets, LIBRA-LiTE uses a liquid metal conductor in a metal case. The tritium breeding blanket would use this same liquid metal, flowing in woven porous tubes. To protect solid surfaces from the target x-rays, the blanket tubes and the focusing magnets are coated with liquid metal. We have done neutronics calculations to determine the lifetime of the metallic case and the frequency at which it must be replaced. The optimum density for the gas in the target chamber has been determined with calculations with the SCATBALL code and has been found to be too low to absorb target x-rays and ions before they reach the focusing magnets and INPORTs.

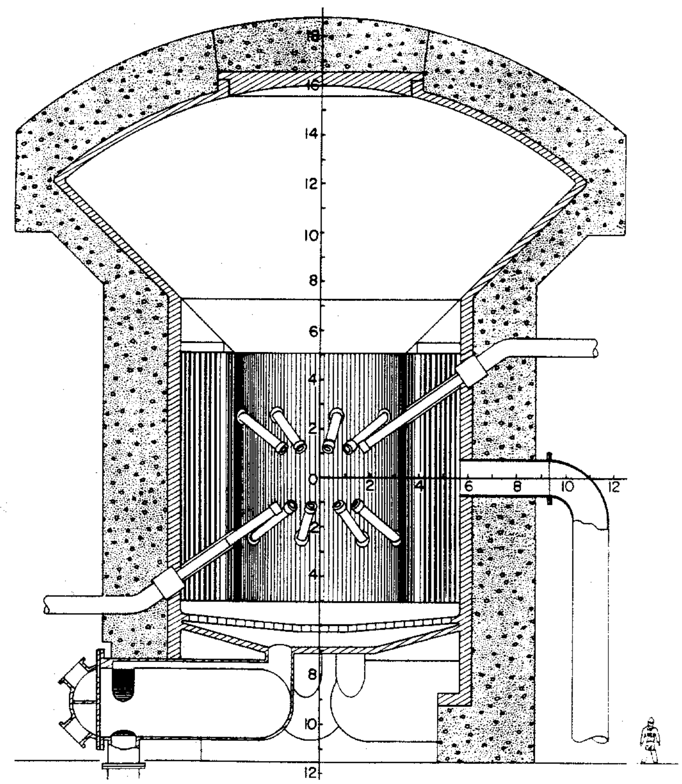

Figure 1. Schematic picture of LIBRA-LiTE target chamber.

We have studied liquid lithium and liquid lithium-lead eutectic as possible conductor and first surface protection fluids. Li is a better electrical conductor, is lighter, produces no unwanted radioisotopes, and allows propagation of the ion beams at higher densities, but PbLi is less chemically active and, therefore, safer. PbLi leads to higher neutron fluxes on the magnets, and therefore increases the frequency at which they are replaced. Based on these considerations we have chosen Li as the liquid metal in LIBRA-LiTE.

Light Ion Driver and Beam Propagation

The pulsed power portion of the driver is essentially the same in LIBRA-LiTE as in LIBRA. Thirty modules with inductive voltage adders driven by magnetically switched water lines and step-up transformers provide roughly 30 MV, 40 ns shaped pulses on 30 diodes at a rate of 5 Hz. The number of modules has been increased from the 18 of LIBRA to provide better symmetry and more credible target performance. The pulses are carefully ramped in voltage to provide time-of-flight bunching of the beam. The total energy provided to all driver modules is 26.6 MJ, of which

Table 1. LIBRA-LiTe and LIBRA Parameters.

	LIBRA	LIBRA-LiTE
Coolant/Breeder	PbLi	Li
Net Power (MWe)	331	1301
Driver Energy (MJ)	4	6
Target Gain	80	100
Target Yield (MJ)	320	600
Rep Rate (Hz)	3	5
Thermal Power (MW)	1161	3380
Gross Thermal Eff. (%)	38	44
Gross Power (MWe)	441	1487
Transport Method	channel	ballistic
Pulsed Power Eff. (%)	37.6	37.6
Transport Eff. (%)	62.5	60.0
Net Driver Eff. (%)	23.5	22.6
Recir. Power (%)	25	12.5
ηG	18.8	22.6
Tritium Breeding Ratio	1.4	1.4
Vessel Life (FPY)	30	30
INPORT Life (FPY)	1.5	2.25
Magnet Life (FPY)	1.5	.75

6 MJ reach the target for a net driver and transport efficiency of 22.6%. We have assumed that the pulsed power efficiency is the same as in LIBRA, or 37.6%, that the ion production efficiency is 80%, and that the ion propagation efficiency is 75%. The last two efficiencies are consistent with LMF parameters [3].

Ballistic propagation of ions in a light ion fusion reactor has potential advantages over propagation using plasma channels, but it requires that focusing magnets be close to the target. Ballistic transport is simpler than channel transport and avoids the problem of electrical breakdown between the plasma channels and the target chamber structure. However, to keep the focusing magnets required for ballistic transport as far as possible from the target, the focal spot at the target is large, which leads to a large required driver energy. Target ignition requires a beam intensity above some minimum value, which we have taken to be 127 TW/cm^2. To achieve this intensity, one adjusts the total beam energy, the positions of the focusing magnets, the microdivergence of the ion beam, and the time of flight bunching of the beam.

We have used the SCATBALL computer code to verify the ability of the ion beam transport system to provide the proper target conditions. SCATBALL is a computer code written at the University of Wisconsin to study the passage of a ballistically focussed ion beam through a gas. The code calculates the envelope of the beam as a function of position. It includes the effects of initial microdivergence, scattering by a background gas and a foil (if one is present), and magnets. The envelope calculation is based on an analytic formulation [4]; SCATBALL also calculates the heating of the background gas by the ion beam. Heating of the background gas by the beam is an important issue because the gas must have a high conductivity for the beam to be stable. We have performed calculations for 30 MeV Li ions and a 1 torr background gas of Li vapor with no foils intersecting the beam. The ion beam and target parameters resulting from these calculations are shown in Table 2. This calculation also predicts that the conductivity of the gas becomes sufficiently high.

Focusing Magnet

Because the electrical resistance of any solid conductor in the focusing magnet would increase rapidly due to radiation effects, flowing lithium was selected as a conductor [6]. The magnet needs a center bore radius of 9 cm and a length of 30 cm. The magnet is a one-turn solenoid with a small gap running the length of the magnet, across which 2.4 volts is applied. The current density in the present design is 7.6 MA/m^2. The

Table 2. Ballistic Ion Transport and Target Parameters.

Gas Density	1 Torr
Total Ion Transport Distance	8.0 m
Beam Micro-divergence	4.0 mrad
Pulse width at Diodes	40 ns
Anode Outer Radius	6.67
Anode Inner Radius	0.53
Drift Length	5.8 m
Focusing Magnet Field	2 T
Beam Radius at Magnet	9.16 cm
Focal Length	2.2 m
Beam Radius on Target	0.9558 cm
Beam Bunching Factor	9
Energy on Target	6 MJ
Target Gain	100

Table 3. LIBRA Target Parameters.

Energy on Target	6 MJ
Gain	100
Yield	600 MJ
X-ray Yield	118 MJ
X-ray Pulse Width (ns)	1.5 ns
Debris Ion Yield	60.9 MJ
Neutron Yield	407 MJ
Gamma Yield	1.74 MJ
Endoergic Losses	12.5 MJ

lithium input and exit pipes are attached to one side of the gap so the fluid entering and leaving the magnet are at the some potential. Internal baffles force the flow to be largely azimuthal. Nuclear heating, MHD effects on the flow, and front surface heating are all being assessed.

Target Chamber Analysis

The target microexplosion releases x-rays, neutrons and ion debris that deposit in the target chamber vapors and structures. We have assumed that the energy partitioning and the emitted spectra are the same as for the ion beam target designed by Bangerter [5]. Some parameters are shown for this target in Table 3. The effects of the neutrons are discussed in the next section. The x-rays deposit in the liquid Li film on the INPORTs and the magnets. They also deposit in the domed roof, but the fluence there is low enough to avoid damage to the surface. A portion of the Li film is rapidly vaporized by the x-rays and the debris ions are deposited in that vapor and in the original Li vapor in the target chamber.

To analyze the behavior of the target chamber gases and vapors, we have used the CONRAD computer code [7]. CONRAD is a one-dimensional Lagrangian radiation-hydrodynamics computer code. Radiation transport is calculated with 20 group radiation diffusion and time-dependent target x-ray and ion deposition is included. The code includes calculation of vaporization and recondensation of materials from an outer wall and heat transfer through the wall. CONRAD simulations provide information on vaporization of wall materials, thermal and pressure loads on the walls, and condensation of vaporized material.

CONRAD simulations have been carried out for vaporization over materials from the surface of the INPORTs and the focusing magnets. Input parameters and results are listed for both calculations in Table 4. The simulations have shown that a shock wave is launched in the vaporized Li that leads to a very high peak pressure imposed on the remaining liquid at the vapor/liquid interface. The peak pressure is several GPa, which is certainly high enough to force a shock into the liquid. The pressure at the vapor/liquid interface on the magnet surface plotted against time is shown in Fig. 2. We have not yet considered the propagation of the shock in the liquid. The impulses on the INPORTs and magnets will be used to con-

Table 4. CONRAD Simulations of Vaporization from INPORTs and Magnets.

	INPORTs	Magnets
Input		
Target to Surface Distance (cm)	345	205
X-ray Fluence (J/cm^2)	78.9	224
Ion Fluence (J/cm^2)	40.7	115
Initial Film Temp. (C)	500	500
Initial Film Thickness (μm)	1000	1000
Initial Vapor Density (10^{15} cm^{-3})	3.55	3.55
Results		
Mass Vaporized (mg/cm^2)	3.47	7.79
Thickness Vaporized (μm)	65.6	147
Remaining Film Thickness (μm)	934	853
Peak Pressure at Interface (GPa)	4.59	7.30
Impulse (Pa-s)	103	188
Final Energy in Vapor (J/cm^2)	49	225
Final Energy in Liquid (J/cm^2)	71	114

sider the mechanical response of these structures and to allow the design of structures with acceptable lifetimes.

Target Chamber and Blanket Neutronics

Neutronics analysis has been performed for LIBRA-LiTE by performing several one-dimensional spherical geometry calculations. The discrete ordinates code ONEDANT [8] was utilized along with 30 neutron-12 gamma group cross section data based on the ENDF/B-V evaluation. A point source is used at the center of the chamber emitting neutrons and gamma photons with the LIBRA target spectrum [1]. The target spectrum takes into account neutron multiplication, spectrum softening and gamma generation resulting from the interaction of the fusion neutrons with the dense target material. The results were normalized to a 600 MJ yield and a repetition rate of 5 Hz.

The blanket is made of banks of INPORT tubes with 0.33 packing fraction. The liquid lithium breeder flows in the tubes which are made of the ferritic steel alloy HT-9. The tubes consist of 2 vol % HT-9 and 98 vol % Li. A 0.5 m thick reflector consisting of 90 vol % HT-9 and 10 vol % Li is used behind the blanket. A minimum local (1-D) tritium breeding ratio (TBR) of 1.3 is required in the INPORT tubes and reflector. This relatively high TBR is required for overall tritium self-sufficiency with a simple roof design that does not have a breeding blanket. In addition, the INPORT tubes are required to provide adequate protection for the front of the reflector (chamber wall) to make it last for the whole reactor life. The peak end-of-life damage in the HT-9 chamber wall is required not to exceed 200 dpa, implying that for 30 full power years (FPY) of operation, the peak dpa rate should not exceed 6.67 dpa/FPY. The inner radius of the chamber wall is determined by the diode location and is taken to be 5.7 m.

Several calculations have been performed for different blanket thicknesses and lithium enrichments. The results are mapped in Fig. 3. In order to satisfy the tritium breeding and wall protection requirements, the design point should be in the box indicated in the upper left corner of the graph. Based on these results, the reference design point was chosen to be a 2.25 m thick blanket with natural lithium. The front surface of the INPORT tubes is at 3.45 m from the target and is exposed to a neutron wall loading of 13.6 MW/m^2. The peak dpa rate in the INPORT units is 90 dpa/FPY implying a lifetime of 2.2 FPY which corresponds to about 3 calendar years (CY) at 75% availability. The peak dpa and helium production rates in the chamber wall are 6.64 dpa/FPY and 25 He appm/FPY, respectively. The chamber wall will last for the whole reactor life. The local TBR is 1.504 and the local nuclear energy multiplication (M_n), defined as the ratio of nuclear heating to the energy of incident neutrons and gamma photons, is 1.242.

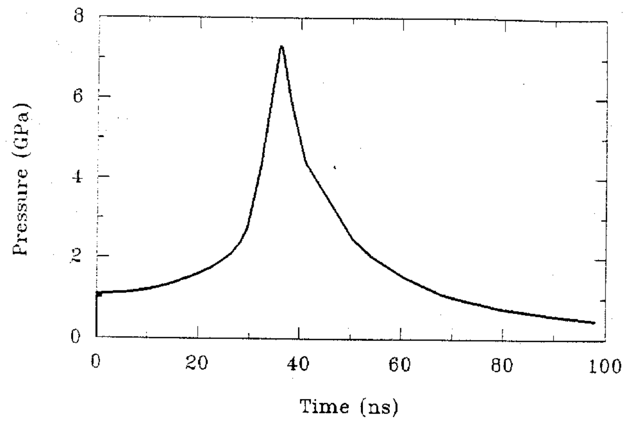

Figure 2. Pressure at vapor/liquid interface on surface of magnets.

Calculations have also been performed to determine the nuclear parameters for the final focusing magnet. Ballistic propagation of the light ions requires the magnets to be located as close as possible to the target. The magnets are 30 cm long and utilize liquid lithium in an HT-9 case. The lifetime of the magnets is determined by radiation damage to the front steel casing. In the reference design, the front surface of the magnet is placed at 2.05 m from the target to achieve a peak dpa rate of 200 dpa/CY implying magnet replacement every one calendar year. The peak helium production is 1700 He appm/FPY. The local TBR and M_n values for the magnets are 0.883 and 1.13, respectively.

The roof of the chamber is a large dome located at 16 m from the target to ensure that it will be a lifetime component. The roof is 50 cm thick and consists of 80 vol % HT-9 and 20 vol % Li. The peak dpa and helium production rates in the HT-9 roof are 6.6 dpa/FPY and 38 He appm/FPY, respectively. The local TBR and M_n values are 0.558 and 1.299, respectively. The depth of the Li pool at the bottom of the reactor was determined to be 75 cm to allow the bottom splash plate, which is 25 cm thick and consisting of 80 vol % HT-9 and 20 vol % Li, to be a lifetime component. The peak dpa and helium production rates in HT-9 are 6.32 dpa/FPY and 29 He appm/FPY, respectively. The local TBR and M_n value are 1.575 and 1.221, respectively. A 2.6 m thick biological shield is used around the chamber to reduce the operational dose rate to 2.5 mrem/hr. The shield consists of 70 vol % concrete, 20 vol % carbon steel C 1020, and 10 vol % He coolant. Using the coverage fractions and local nuclear parameters for the different reactor regions surrounding the target, the overall reactor TBR and M_n were determined to be 1.396 and 1.217, respectively. Taking into account surface heating by the x-rays and debris, the overall reactor energy multiplication, defined as the ratio of the total thermal power to the fusion power, is 1.127 and the total thermal power is 3380 MW.

Conclusion

We are in the midst of analyzing the LIBRA-LiTE power plant design. Ballistic propagation with magnetic focusing has been chosen for this design. We have attempted to extend the life of the focusing magnets by using a liquid lithium conductor and by placing them as far a possible from

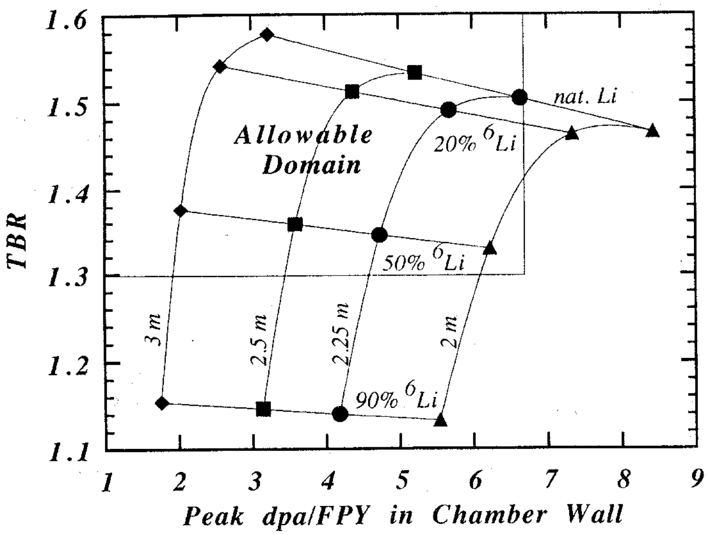

Figure 3. Tritium breeding ratio and dpa rate for different design options of LIBRA-LiTE blanket.

the target. The placement of the magnets requires low diode microdivergence and a high beam bunching ratio to avoid a very high driver energy. We have done neutronic and vaporization analysis to date. Mechanical response analysis and balance of plant design will be done in the future. Maintenance schemes are currently under study.

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Bibliography

[1] B. Badger, et al., "LIBRA - A Light Ion Beam Fusion Conceptual Reactor Design," University of Wisconsin Fusion Technology Institute Report UWFDM-800, 1989.

[2] G.L. Kulcinski, et al., "The INPORT Concept - An Improved Method to Protect ICF Reactor First Walls," J. Nucl. Materials, vol. 103 & 104, p. 103, 1982.

[3] J.J. Ramirez, et al., "A Light Ion Beam Driver for the Laboratory Microfusion Facility," Fusion Tech., vol. 19 2A, p. 664, 1991.

[4] C.L. Olson, "Achromatic Magnetic Lens Systems for High Current Ion Beams," Proc. 1988 Linear Accelerator Conference, CEBAF Report 89-001, 1989, p. 34.

[5] R.O. Bangerter, "Targets for Heavy Ion Fusion," Fusion Tech., vol. 13, p. 348, 1988.

[6] D.C. Steiner, R.C. Block, and B.K. Malaverya, "The Integral Blanket - Coil Concept Applied to the Poloidal Field and Blanket Systems of a Tokamak Reactor," Fusion Technology, vol. 7, p. 66, 1985.

[7] R.R. Peterson, J.J. MacFarlane, and G.A. Moses, "CONRAD – A Combined Hydrodynamic-Condensation/Vaporization Computer Code," University of Wisconsin Fusion Technology Institute Report UWFDM-670, 1988.

[8] R. O'Dell et al., "User's Manual for ONEDANT: A Code Package for One-Dimensional, Diffusion-Accelerated, Neutral Particle Transport," Los Alamos National Laboratory, LA-9184-M, 1982.