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EVOLUTION OF LIGHT ION DRIVEN FUSION POWER PLANTS LEADING TO THE LIBRA-SP DESIGN

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ABSTRACT

The use of light ion or electron beams to compress matter to the densities required for fusion has been proposed for more than 20 years. In the past ten years, a series of light ion beam power plant conceptual designs have been published under the generic name LIBRA. Considerable advances in both physics and technology have allowed major improvements from the design performance of the earliest LIBRA 330 MW_e power plant to the more recent 979 MW_e LIBRA-LiTE, and the 1000 MW_e LIBRA-SP reactors. The recent declassification of target designs allows more realistic target spectra, gains, and injection parameters to be analyzed. The pulsed power driver technology has matured to the point that Helia induction technology can be tested in the laboratory under single pulse conditions and confidently extrapolated to LIBRA repetition rates. New concepts for protecting the first structural wall of the reactor have been developed; the use of flexible INPORT (<u>IN</u>hibited Flow in <u>POR</u>ous <u>T</u>ube) and rigid PERIT (PErforated RIgid Tube) units allow the reflector and first wall to last the lifetime of the power plant. The use of PbLi eutectic alloy has greatly improved the safety features of these reactors and the economics of all three compare very favorably to the tokamak, laser, and heavy ion beam reactors.

I. INTRODUCTION

Since the first proposal, in the early 1970's, to use energetic electrons to implode targets in ICF reactors[1] there have been several advances in the field of particle beam fusion. The early reactors were relatively high rep rate, low yield systems (see Fig. 1) with little detail on the driver technologies to be used. There were efforts in both the US and USSR. Novel ideas, in this early period, to protect the first wall from the target debris included "moving belts"[2] and Li "rain".[3]

In the 1980's, the driver beam was changed to 6-8 MeV proton beams which were used to drive targets to higher yields and consequently required lower rep rates.[4] Channel transport schemes were then the most popular means of transporting the ions to the target. The use of porous "INPORT" units[5] was applied in that time period to protect the first wall as was the use of internal gas protection.[6] Both of these latter techniques were used to reduce the diameter of the reaction chamber to 4-5 m. The scope of the international effort was expanded to Europe (Germany) and Asia (Japan).

As the physics of beam propagation and target interactions improved in the 1990's, scientists[7] used higher atomic weight ions (Li, and suggested even higher elements such as F) at higher voltages (30-40 MV). The use of Helia inductive voltage adder technology became standard and there was a great deal of analysis for ballistic and self-pinched transport of ions.[8] Some of this work is to be verified on the SABRE facility at SNL in the US.

The LIBRA class of reactors, which represent a collaboration between the US and Germany, have embodied the most recent changes and currently serve as the "flagship" of the light ion beam (LIB) community's reactor design program. The goals of the LIBRA project are:

- To develop a *self-consistent* conceptual design of a light ion beam driven fusion power plant.
- To evaluate the potential of light ion fusion power plants for economically attractive *small* power plants.

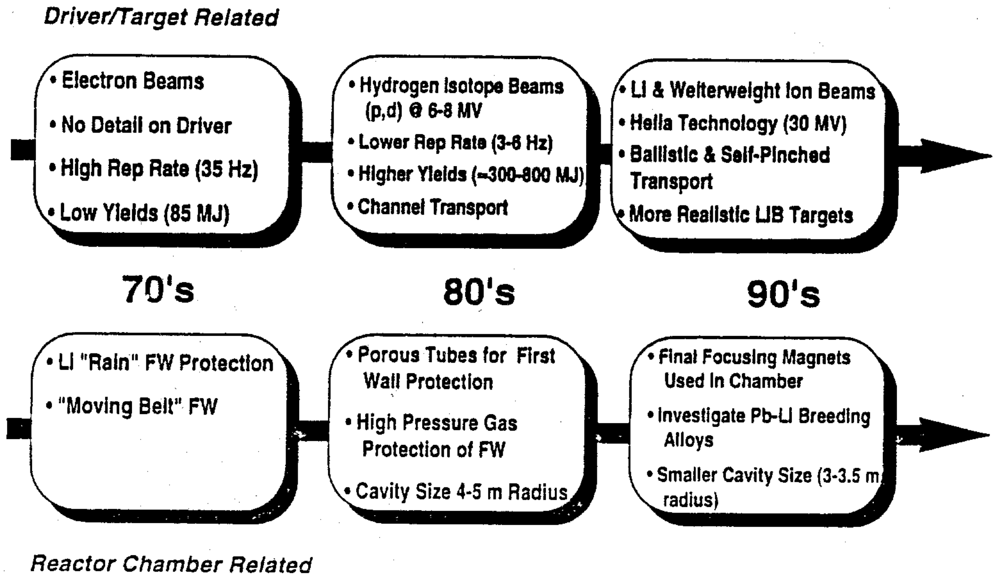

Fig. 1. The historical trends in light ion beam driven fusion power plant designs have reduced the size and increased their economic and safety attractiveness.

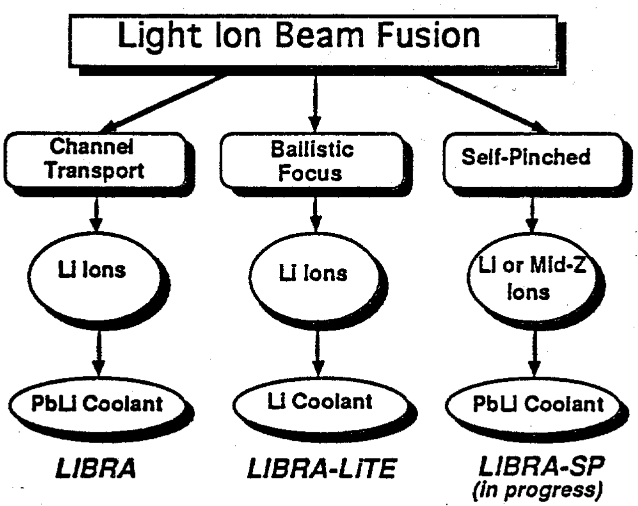

Fig. 2. The method of transferring the ion beam to the target has been the main difference in the LIBRA class of power plants. See Fig. 3 for a schematic for the various mechanisms.

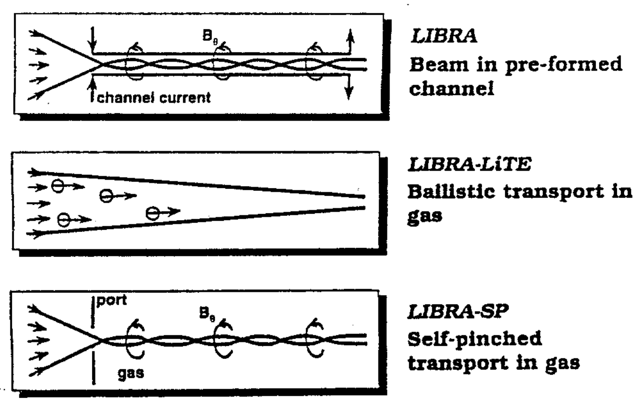

Fig. 3. Schematic of the various transport schemes used in the LIBRA class of light ion driven fusion power plants.

II. GENERAL FEATURES OF THE LIBRA CLASS OF FUSION POWER PLANTS

The main difference in the LIBRA class of reactors is the mode by which the high energy imploding ions are transferred from the diode to the target (see Fig. 2). In LIBRA,[9] completed in 1989, channel transport of the 30 MeV Li ions in preformed channels was utilized (see Fig. 3). The high background chamber gas pressure allowed the use of a PbLi eutectic alloy coolant inside the chamber.

The difficulty in forming a narrow plasma channel in LIBRA prompted the designers to investigate the ballistic transport mechanism in LIBRA-LiTE[10] completed in 1991. This transport mechanism required substantial final focusing magnets inside the reaction chamber which, in turn, had to be designed to withstand large neutron fluxes. In order to avoid excessive scattering of the ions, a low cavity gas pressure of low Z atoms (i.e., Li) is utilized requiring that the internal coolant be Li instead of the heavier PbLi.

While the focal spots could be kept small with ballistic focusing, the use of magnets in high radiation fields was not fully accepted and the safety considerations associated with liquid Li prompted another switch in 1994

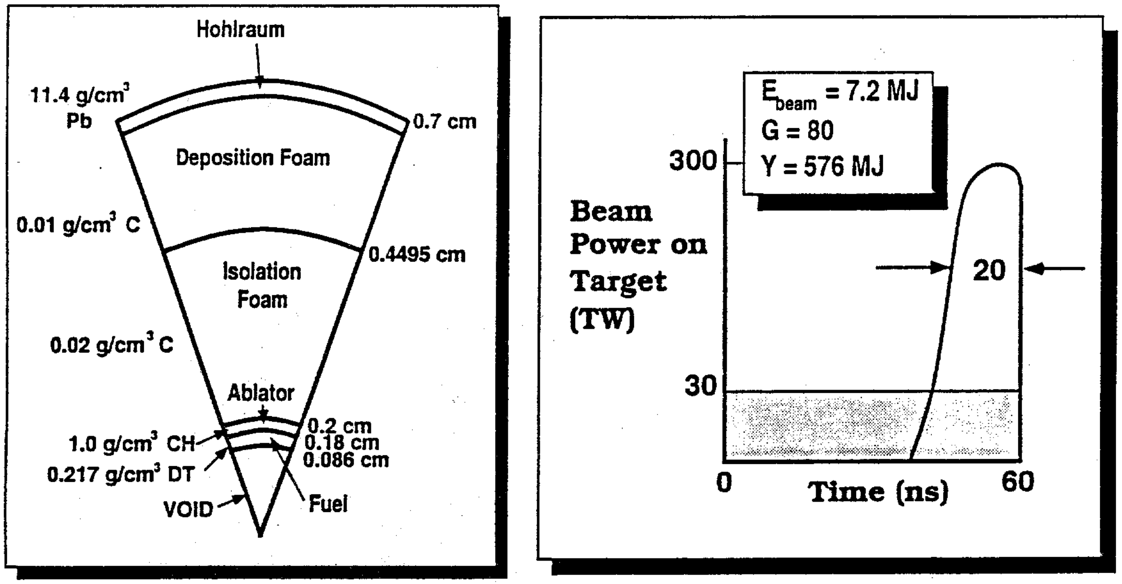

Fig. 4. Schematic of the target used for the LIBRA-SP power plant design along with the power profile used to drive the internally pulse shaped target to ignition and burn.

Table I

Key Parameters for the LIBRA Class of Light Ion Beam Driven Fusion Power Plants

Parameter	LIBRA	LIBRA-LITE	LIBRA-SP
Focus Mechanism	Channel Transport	Ballistic	Self-Pinched
Net Electric Power, MWe	331	979	1000
Li Ion Beam Energy to Target, MJ	4	6	7.2
Target Yield, MJ/Rep Rate, Hz	320/3	600/3.9	576/3.7
Coolant/Breeder	PbLi	Li	PbLi
INPORT/PERIT Material	SiC	Steel	Steel
Secondary Heat Transfer Fluid	He	Organic	He

*Use 25–35 MeV Li ions from Helia type driver

to the use of self-pinched beam transport, LIBRA-SP. The safety concerns with Li were solved by utilizing the PbLi alloy again.

The key parameters of the three designs are given in Table I. Aside from the coolant and beam transport differences, it can be seen that the ability of light ion beam (LIB) systems to operate at low power levels was demonstrated in the 330 MW_e LIBRA design. The other two designs were conducted at approximately the 1000 MWe level to be more consistent with current tokamak, laser and heavy ion beam conceptual designs.

Other differences apparent from Table I include increasingly higher ion beam energy on target (i.e., 4 vs. 6 vs. 7.2 MJ) and somewhat different yields depending on the evolving target physics that was used during each study. The method of protecting the first walls evolved from flexible SiC INPORT units (to be described later) in LIBRA, to flexible steel INPORT units in LIBRA-LiTE and more recently, perforated rigid steel (PERIT) units in LIBRA-SP. Finally, helium was used as a secondary heat transfer fluid in LIBRA and LIBRA-SP while a high operating temperature organic fluid was used with the Li in LIBRA-LiTE.

III. TARGET AND DRIVER PARAMETERS

The original LIBRA and LIBRA-LiTE designs were forced to use targets originally designed for heavy ion beam reactors because of classification in the US. The generic target chosen was that analyzed for HIBALL.[11] However, recent declassification[12] of light ion targets has allowed the use of more realistic configurations such as that shown in Fig. 4. If the target in Fig. 4 is illuminated with the beam power shown in that figure (from 12 prepulse beams and 12 full power beams), then the internal pulse shaping of the x-ray flux to the center capsule should be sufficient to achieve a gain of 80 (see Fig. 5 for the predicted comparison of the LIBRA targets compared to the targets from other ICF conceptual reactor designs.)

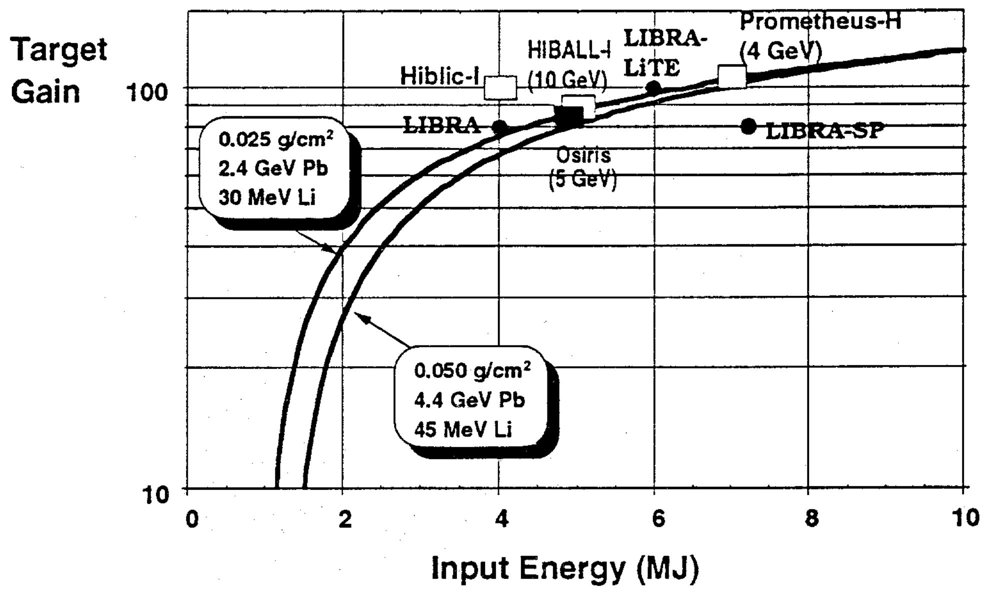

Fig. 5. The performance of targets that rely on internal pulse shaping is slightly degraded from the indirect drive ICF target designs.

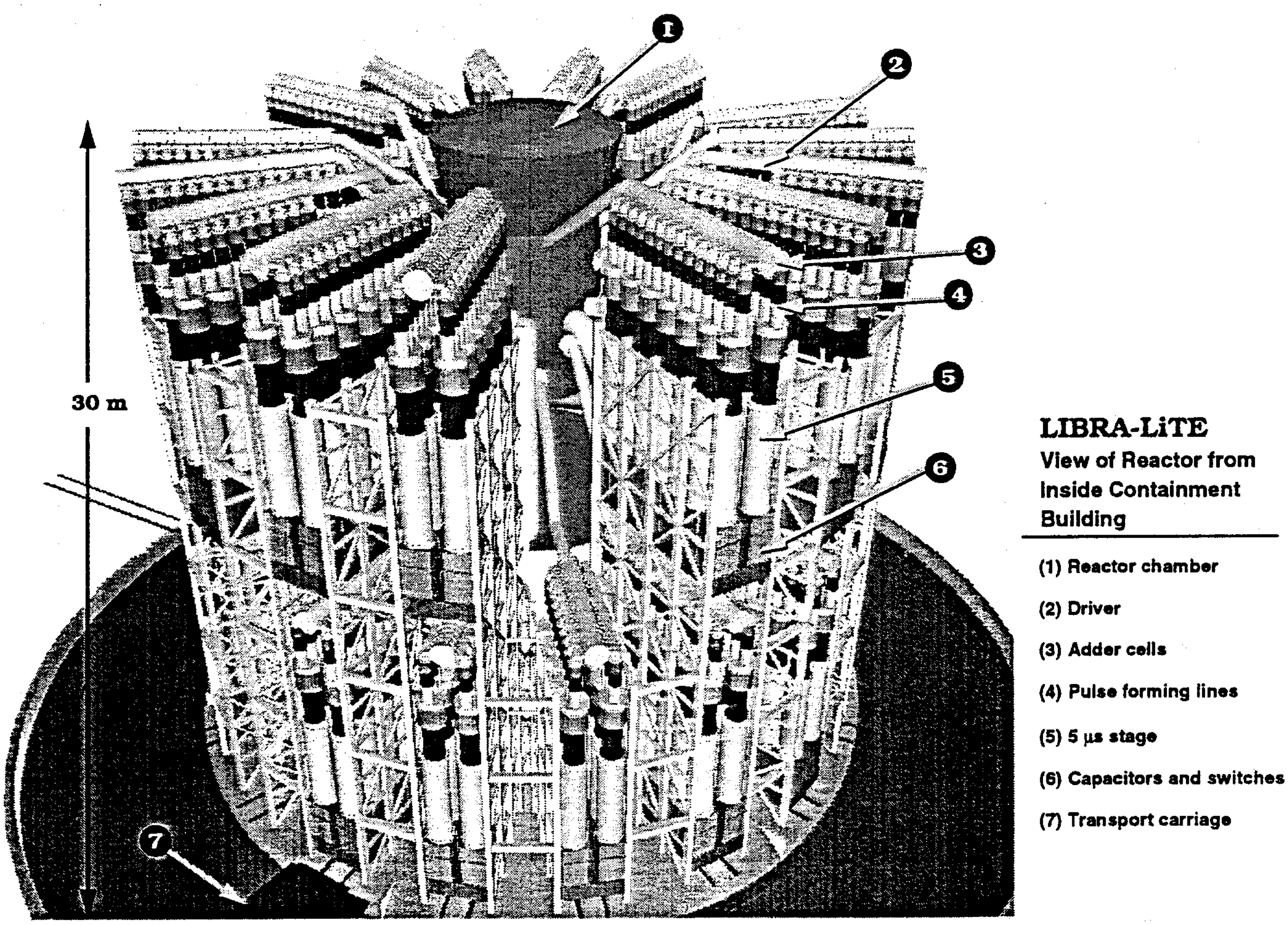

Fig. 6. Isometric view of the LIBRA-LiTE reaction chamber surrounded by 30 pulsed power units. Note the double stacking arrangement and the size of the reactor in the center (1).

Table II

Summary of the Cavity Conditions in the LIBRA Designs

	LIBRA	LIBRA-LiTE	LIBRA-SP (Preliminary)
Initial Gas Conditions			
Temperature	500°C	500°C	550°C
Species	He	He	He
# Density	3.55×10^{18} cm^{-3}	3.55×10^{16} cm^{-3}	7.4×10^{16} cm^{-3}
Conditions at INPORTs or PERITs			
Peak Pressure	100 GPa	4.6 GPa	100 GPa
Pulse Width (FWHM)	1 ns	8 ns	1 ns
Total Impulse	125 Pa-s	100 Pa-s	TBD
Vaporization	7 μm PbLi	66 μm Li	21 μm PbLi

An example of how the pulsed power driver units are placed around the reaction chamber is shown in Fig. 6 for the LIBRA-LiTE reactor. The main difference for the LIBRA-SP design is that there would be fewer units (24 vs. 30 for LIBRA-LiTE).

The net driver efficiency (energy on target/prime energy storage) is very much a function of gross electrical conversion efficiency to the diode, the conversion of electrical energy in the diode to ions, and the transport efficiency of the ions to the target. Figure 7 shows how those factors are related for the LIBRA, LIBRA-LiTE, and LIBRA-SP designs. Note that the overall net efficiency of the self-pinched mode of ion transport is estimated to be ≈30%,[13] that of channel transport is 23.5%,[9] and only 18%[14] for the ballistic transport mode.

IV. CAVITY CONDITIONS

A cross section of the reaction vessel for the LIBRA-SP design is given in Fig. 8. Only 2 of the 24 beam lines are shown in the schematic along with a duct to the expansion chamber, the curved tubes which carry the PbLi coolant from the top header to the pool below, and the PbLi/He heat exchanger below the chamber. The roof is far enough away to be a lifetime component.

One of the unique engineering problems faced by all LIB reactor designers is that of containing the ≈600 MJ blast from the target if it is successfully ignited. In the past, the shock wave and neutron flux from the exploding target was absorbed by flexible, porous woven tubes of SiC (LIBRA) or steel (LIBRA-LiTE) such as those shown in Fig. 9.

In spite of the many advantages of the INPORT concept (see Refs. 9-11 for a fuller discussion), a considerable axial tension must be applied and maintained on the woven tubes to reduce radial deflection in response to the impulse from vaporized liquid and microexplosion. This is particularly difficult when the coolant is heavy like PbLi.

The solution to this problem in LIBRA-SP was to replace the flexible woven porous tubes with rigid, curved steel tubes that have small slits machined into them at appropriate angles. These slits, aimed at the inner chamber are designed to release a continuous sheet of coolant on the front tubes to intercept the blast wave (see Fig. 10).

The cavity conditions in each of the last 3 LIBRA designs are listed in Table II. Note that helium gas is used in all the designs but that the background pressure is 100 torr in LIBRA, 1 torr in LIBRA-LiTE, and 2 torr in LIBRA-SP. The pressure, impulse and vaporization conditions vary with pulse width and type of coolant.

Table III

The Neutronic Properties of the LIBRA Designs are Quite Attractive

	LIBRA	LIBRA-LiTE	LIBRA-SP (Preliminary)
Neutron Wall Loading (MW/m^2)	6	10.6 (INPORT) 29 (Magnets)	7.2
Breeder	PbLi	Li	PbLi
% ^{6}Li	90	7.4	90
Tritium Breeding Ratio	1.36	1.41	1.48
Overall Energy Multiplication	1.17	1.12	1.18
Damage to INPORT/PERIT Units (dpa/FPY)	60	68	87
Damage to Steel Chamber Walls (dpa/FPY)	6.7	5	3.9

V. NEUTRONIC PERFORMANCE

The simple geometric coverage inside the LIBRA chambers, in addition to the close proximity of an abundance of Li and PbLi alloys, allows a superior neutronic performance in the LIBRA reactors. The main parameters are listed in Table III for the three light ion beam reactors.

Note that the dpa damage is not proportional to the wall loading alone because the PbLi multiplies the number of neutrons more effectively than Li and the dpa cross sections of SiC are different than those of steel. It is also important to note that none of the designs has trouble breeding (e.g., TBR's range from 1.36 to 1.48) and the overall energy multiplication (total recoverable power

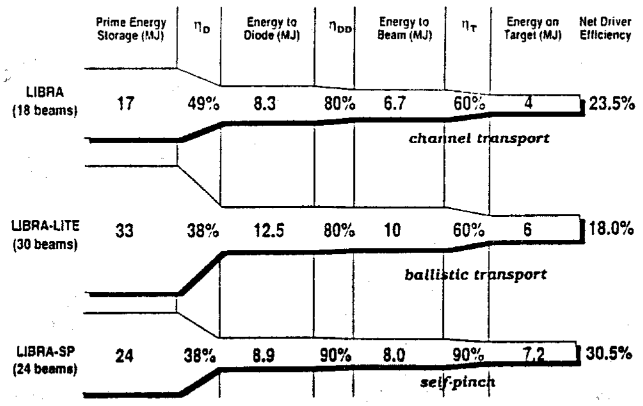

Fig. 7. The use of Helia driver technology and Li ion applied B diodes allows efficient energy transport to the target, especially in the self-pinched mode.

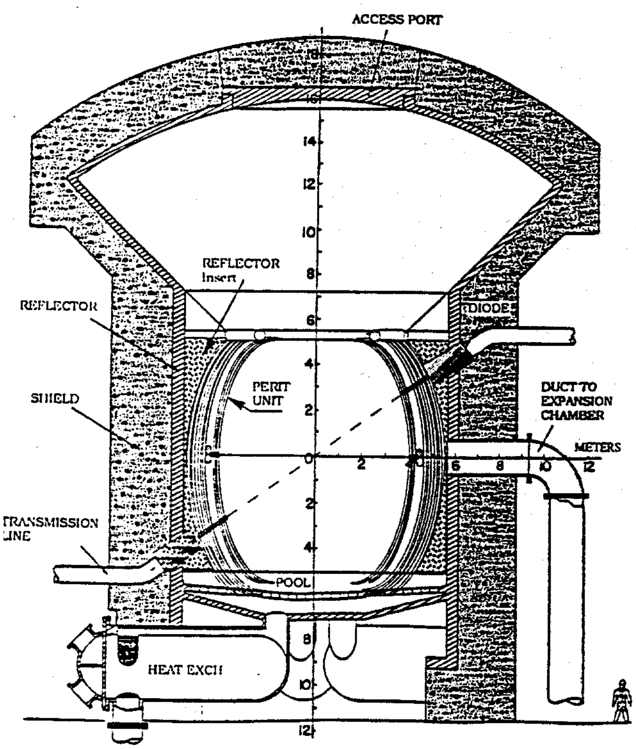

Fig. 8. The cross sectional view of the LIBRA-SP reaction chamber showing the placement of the Li diodes and the perforated rigid tubes (PERIT's) which absorb most of the target debris and neutrons emitted from the target.

from chamber/fusion power) is a respectable 1.12 to 1.18. The neutron wall loadings on the INPORT or PERIT units ranges from 6 to 11 MW/m^2 resulting in 60 to 90 dpa/FPY on those units. Such damage rates will require frequent replacement of the protective units (perhaps on a 2-3 year basis).

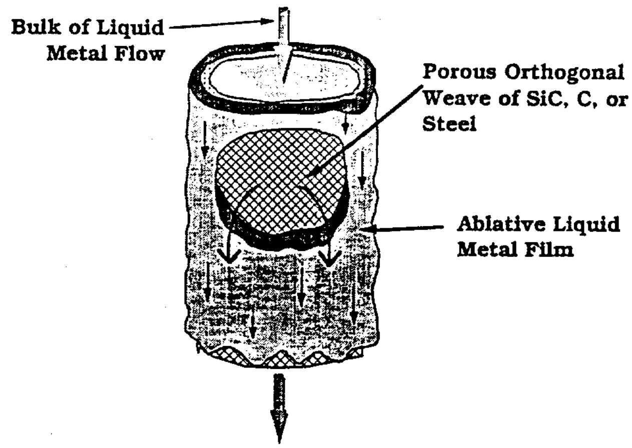

Fig. 9. A schematic of the flexible woven inhibited flow porous tube (INPORT) units displaying how the wetted surface of the tubes absorb the x-rays and target debris while the bulk of the liquid flowing through the tube absorbs the energy and mitigates the isochoric heating of the neutrons.

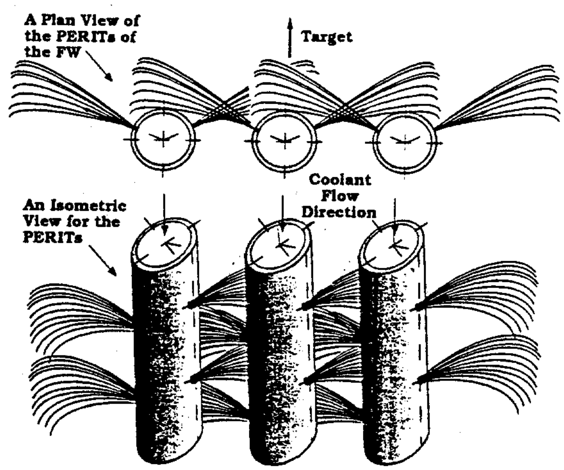

Fig. 10. Two views of the PErforated RIgid Tube (PERIT) units specially designed for the LIBRA-SP power plant. The small slits, pointing slightly forward, provide enough PbLi sheet in front of curved tubes to mitigate the shock wave and reduce the amount of x-ray induced vaporization from the tubes.

VI. TRITIUM INVENTORIES

The inventory of tritium in any ICF power plant can be conveniently divided into:

- The target fabrication facility
- Reactor hall
- Fuel processing.

The quantitative numbers for each of the LIBRA reactors are listed in Table IV.

Table IV
The Active Tritium Inventories in the
LIBRA Reactors are Relatively Low

		grams	
Location	*LIBRA (PbLi)*	*LIBRA-LiTE (Li)*	*LIBRA-SP (PbLi)*
Target Fabrication Facility	134	193	198
Reactor Hall			
Targets (1 hr)	21	50	53
Breeder	0.4	230	2
INPORT/PERIT Units	150	~0	~0
Exhaust	1.3	7	4
	173	287	59
Fuel Processing			
Purification	1.3	4	2
Isotope Separation	45	35	35
	46	39	37
Total Active	353	519	294
Max. Exposure at fence if all T_2 were released–WB early dose	0.7 Rem (7 mSv)	1 Rem (10 mSv)	0.6 Rem (6 mSv)

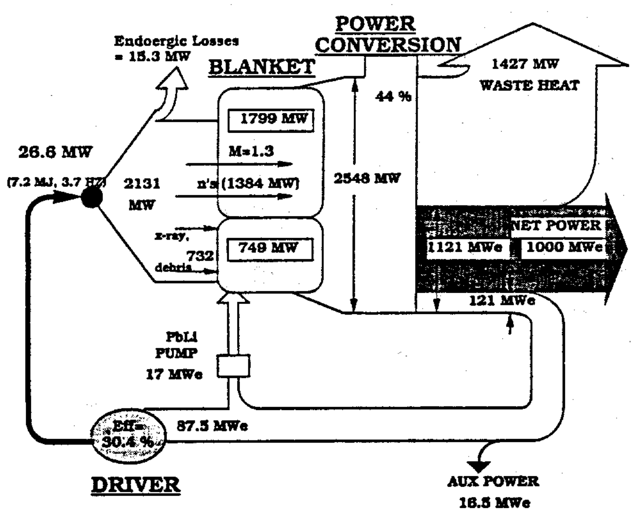

Fig. 11. The power flow diagram for the LIBRA-SP power plant.

Note that even though the power level of the LIBRA reactor was only 330 MW_e vs. LIBRA-SP at 1000 MW_e, the total active inventory is actually less in the LIBRA-SP design. This seeming contradiction can be explained by the fact that the target fabrication scheme is more efficient in LIBRA-SP, and because tritium is far less soluble in steel than in SiC. The end result is that the maximum whole body early exposure at the fence if all the T_2 were released is in the range of 0.6 to 1 Rem.

VII. POWER CYCLE CONSIDERATIONS

The 1000 MWe of net power is produced from 2131 MW of fusion power (see Fig. 11). The gross conversion of the energy in 550°C PbLi to electricity is ≈44%. With a net recirculating fraction of ≈11% there is enough auxiliary power to pump the heavy PbLi coolant and drive the pulsed power units to 7.2 MJ at a 3.7 Hz rate.

Table V

The Direct Capital Costs of the LIBRA
Series of Reactor Designs

	M$ (1993)		
	LIBRA	*LIBRA-LiTE*	*LIBRA-SP (prelim.)*
Driver	524	514	343
Total (incl. driver)	1157	1786	1528
Unit Direct Capital Costs ($/kWe)	3495	1835	1528
Net Power (MWe)	331	973	1000

VIII. ECONOMIC PERFORMANCE

Because of the much higher efficiency of wall plug energy to ions on the target in LIBRA-SP, smaller pulsed power units can be purchased. This allows the driver costs to be reduced by 33% from those needed in LIBRA-LiTE for approximately the same net power output (see Table V). The total direct capital cost of LIBRA-SP is less than half that of the earlier 330 MWe LIBRA design and 17% less expensive compared to LIBRA-LiTE at about the same power level.

A comparison of the cost of light ion reactor studies to previous tokamak, laser, and heavy ion designs also shows that light ions retain their attractive economic performance (see Fig. 12). For example, the LIB designs are a full 30% lower than recent tokamak designs, 20% lower than laser power plants and ≈10% lower than the recent HIB designs.

IX. CONCLUSIONS

The LIBRA class of ICF power plants display (compared to heavy ion beam and laser designs):

- Comparable technological readiness
- Adaptability to lower power levels.
- Simplicity of design
- Attractive safety features
- Potentially the lowest COE.

However, there are two major concerns related to this form of inertial confinement fusion (in addition to the normal target fabrication, injection, and tracking concerns of all ICF concepts):

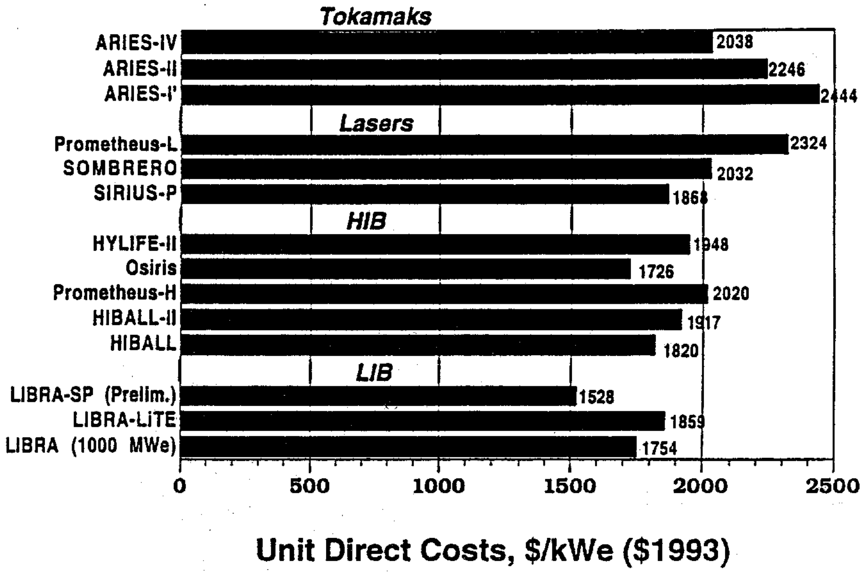

Fig. 12. The direct unit cost of the LIBRA reactors compares very favorably with other ICF and MCF DT power plants at the 1000 MWe level.

1. The transport of ions in a narrow beam to the target on a repeatable basis must be demonstrated experimentally. At the present time propagation in the self-pinched mode seems promising.
2. The light ion beam plants depend on the successful performance of internal pulse shaping in spherical targets. Experimental verification of this mechanism is vital.

If these two problems can be solved in the next 10-15 years, then electricity from DT fuels could be available from light ion driven fusion power plants in the second decade of the 21st century.

ACKNOWLEDGMENTS

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