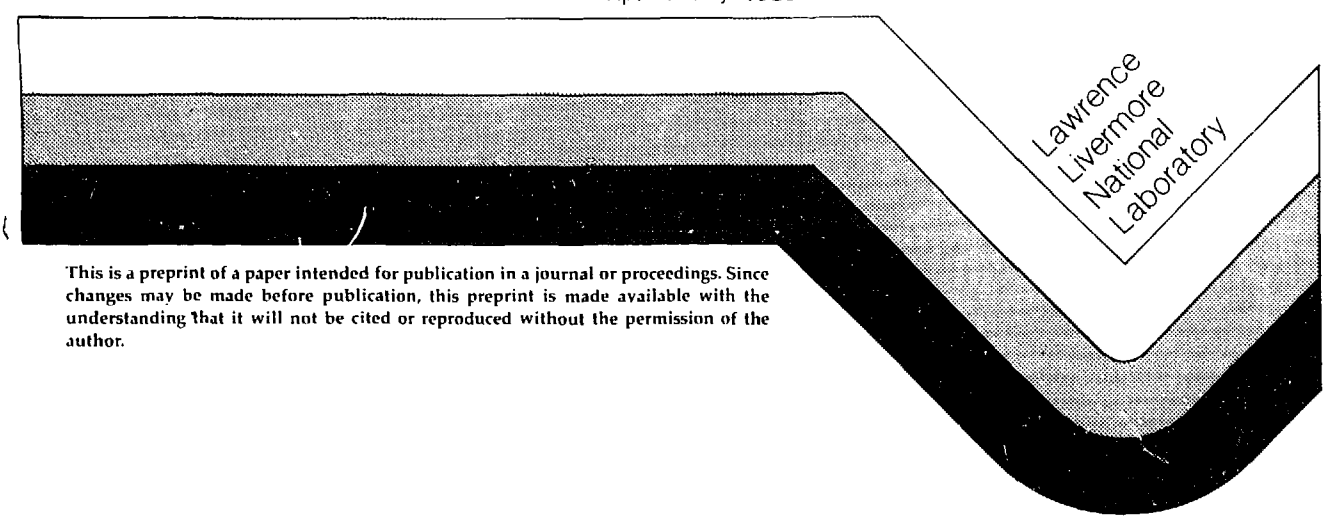
UCRL- 91643
PREPRINT
CONF-850310--89

The Pulse*Star Inertial Confinement Fusion Reactor

J. A. Blink
W. J. Hogan

This paper was prepared for submittal to
the 6th ANS Topical Meeting on Technology
of Fusion Energy, San Francisco, CA
March 3-7, 1985.

April 15, 1985



DISCLAIMER

THE PULSE*STAR INERTIAL CONFINEMENT FUSION REACTOR*

UCRL--91643

DE85 010940

J. A. Blink and W. J. Hogan
Lawrence Livermore National Laboratory
University of California
P.O. Box 5508, L-487
Livermore, California 94550
415/422-8258

ABSTRACT

Pulse*Star is a pool-type ICF reactor that emphasizes low cost and high safety levels. The reactor consists of a vacuum chamber (belljar) submerged in a compact liquid metal ($Li_{17}Pb_{83}$ or lithium) pool which also contains the heat exchangers and liquid metal pumps. The shielding efficiency of the liquid metal pool is high enough to allow hands-on maintenance of (removed) pumps and heat exchangers. Liquid metal is allowed to spray through the 5.5 m radius belljar at a controlled rate, but is prohibited from the target region by a 4 m radius mesh first wall. The wetted first wall absorbs the fusion x-rays and debris while the spray region absorbs the fusion neutrons. The mesh allows vaporized liquid metal to blow through to the spray region where it can quickly cool and condense. Preliminary calculations show that a 2 m thick first wall could handle the mechanical (support, buckling, and x-ray-induced hoop) loads. Wetting and gas flow issues are in an initial investigation stage.

INTRODUCTION

Although early ICF reactor designs (such as HYLIFE) appeared to be feasible, safe, and environmentally benign, they were probably too expensive to compete with coal or light water fission reactors (LWRs). Much of the high cost of HYLIFE (and LWRs) is due to extensive pipe runs and buildings. Pulse*Star (Fig. 1) reduces these costs by using a compact pool type design. The power density within the Pulse*Star pool (which includes the four primary pumps and the eight steam generators) is 29 times that within an LWR containment building.[1] The liquid metal inventory in Pulse*Star (3400 m^3) is only a factor of two higher than in HYLIFE because of the elimination of the long liquid metal piping runs.

BALANCE OF PLANT ISSUES

In the last two years, the focus of our efforts has been on balance of plant issues, since the balance of plant is the area that drove HYLIFE's cost. Steam generators and pumps have been designed for both $Li_{17}Pb_{83}$ (LiPb) and pure lithium cooled versions of Pulse*Star. (These designs are compared in a detailed paper later in this meeting.)[2]

Two major issues remain for the LiPb balance of plant: 1) the control of ^{210}Po created in neutron reactions with lead, and 2) the containment of tritium. The first issue is treated in detail in another paper at this meeting[3] and will not be discussed further here.

Because tritium is not very soluble in LiPb, concern has been expressed that tritium will easily diffuse into the steam supply in a Pulse*Star reactor and escape into the environment at an unacceptable rate. While acceptable tritium leakage rates for a fusion reactor are still subject to much debate, values of 10 to 500 Ci (1-50 mg) per day have been widely used for conservative calculational purposes. About 1.4 kg of tritium are injected into the chamber each day, and this implies very stringent measures might have to be taken to reduce tritium leakage to an acceptable level.

The tritium vapor in the Pulse*Star chamber is probably in equilibrium with the tritium dissolved in the LiPb for the following reasons. Some LiPb vaporizes with each fusion pulse and mixes well with the tritium, deuterium and helium gases from the target. This mixture is in close contact with the fine LiPb droplets in the spray zone as the LiPb recondenses. Further, tritium and helium are produced in the LiPb by neutron

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

jsw

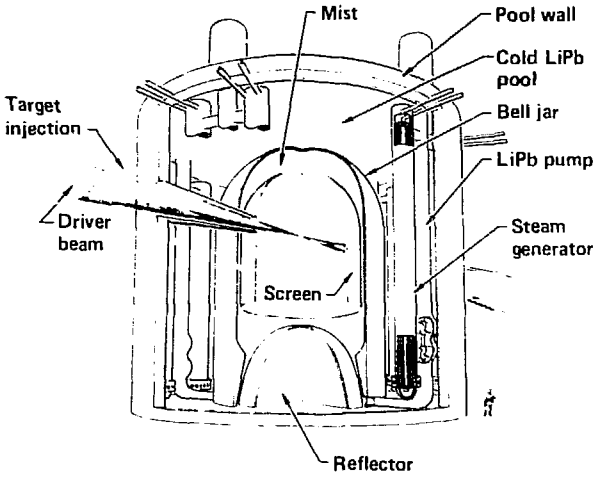


Fig. 1. The Pulse*Star Reactor

reactions in the same spray zone. Each LiPb droplet experiences many fusion pulses as it falls to the bottom of the chamber.

The equilibrium atomic concentration of tritium in the LiPb is:

$$C_T = P_T/K_S \qquad (1)$$

where P_T is the tritium pressure in the chamber and K_S (Sievert's constant) varies between 1.0 and 1.3 $torr^{1/2}$/appm for 500°C to 400°C LiPb. Last year[1], an upper limit of 1.7 (10^{-3}) torr was established for the tritium pressure in the chamber to minimize the tritium release in the event of a spill of the LiPb. Using this pressure in Eq. 1, we find a tritium concentration of 0.034 appm in the LiPb or a tritium inventory of ~20 g in the 3.2 (10^{10}) g LiPb inventory. This low value is an advantage from the standpoint of accidental release. However, the entire LiPb inventory circulates through the heat exchangers over 500 times a day, and, therefore, there is a potentially large steady state leakage problem.

In the absence of any tritium extraction process in the LiPb circulation loop, we can expect 1.7 (10^{-3}) torr to be the driving pressure for tritium on the LiPb side of the heat exchangers. The temperature of the tube wall varies from about 500°C at the top to about 400°C at the bottom. Using the DIFFUSE code, M. Baskes[4] has calculated the tritium permeation rate through a 4.8 mm Fe wall for the above driving pressure, with wall temperatures of 400°C to 500°C and ΔT's of 0 to 50°C. Values between 2.5 and 4.5 mg/m^2 per day were obtained. Using an average value of 3.1 mg/m^2 for the 14,700 m^2 area of the heat exchangers results in an estimate of 50 g/day (neglecting back diffusion) or three to four orders of magnitude greater than the present goals.

Several methods of reducing the tritium leakage to the environment have been proposed:

- o Dilution of the chamber gases with hydrogen or helium,
- o Adding a liquid getter to the LiPb to trap tritium,
- o Removing tritium from the LiPb with counterflowing He,
- o Using double-walled heat exchanger tubes with an oxide layer and/or flowing gas sweep system,
- o Introducing a liquid Na intermediate loop and cold trapping tritium from the Na,
- o Removing tritium from the water in the steam cycle,
- o Substituting liquid lithium for LiPb as the coolant.

All of these methods are being examined quantitatively.

FIRST WALL AND BLANKET ISSUES

Since an economical balance of plant appears to be feasible, emphasis is shifting to design of the portion of the reactor that absorbs the fusion energy. This region includes a 4 m radius, porous, wetted first wall and a 5.5 m radius belljar that separates the inner vacuum from the outer cold pool. The liquid metal flows through nozzles in the belljar to form a mist between the first wall and belljar The driver beams are protected by beam tubes which terminate at the first wall. The liquid metal mist is heated as it falls to the inner (hot) pool. The mist also wets the porous first wall and acts as a cooling and condensation surface for Li or LiPb that is ablated from the first wall by the fusion x rays and debris.

The key component is the porous first wall which has three design constraints. Its inner surface must be re-wetted within the 0.2 sec interpulse time (by flow from the exterior mist). It must withstand the recoil caused by the x-ray/debris driven ablation (~2 cm of metal thickness are required). Finally, it must allow the ablated lithium or LiPb to pass easily (without choking) to the mist region, thereby assuring re-establishment of the chamber vacuum.

Mechanical design of a porous structure is underway. Wetting and flow experiments in ETEC's lithium loop are planned. Finally, research at the University of Wisconsin on hot gas flow through a network of structures[5] will be applied to the gas removal issue. Preliminary calculations on the first two design constraints are summarized below.

Injection Velocity and Required Head. The mesh-to-belljar space is 1.5 m based on 50% packing fraction and 75 cm of neutron protection for the belljar. (A larger space will be required if 50% packing fraction cannot be attained in practice). The interpulse time is 0.2 sec, therefore, the fluid radial velocity (ignoring gravity) is 1.5/0.2 = 7.5 m/s for completely new fluid to reach the mesh between pulses. The total nozzle area is 22/7.5 = 2.93 m^2 which is 0.9% of the area of the belljar (a 5.5 m hemisphere mounted on a 4 m high, 5.5 m radius cylinder). The head required is $\rho v^2/2$ = 260 kPa or 2.8 m of LiPb height above the nozzle (neglecting nozzle pressure drop). Variable pressure drop nozzles can be used to eliminate the extra head available to the lower nozzles; alternatively, a higher fluid velocity in the lower region could be acceptable.

Buckling Load on the Mesh First Wall from Impacting Liquid. The liquid LiPb impacting on the outside of the mesh creates buckling loads. The pressure is the momentum change per unit area per unit time. For sticking (not bouncing) liquid on a 4 m radius mesh, the pressure is 7.55 kPa (1.1 psi); i.e., (22 m^3/s) (9200 kg/ m^3)(7.5 m/s)/201 m^2. The mesh could be supported by cables or beams from the belljar. For a 100 MPa stress in the supports, the support area fraction is 0.008%. Stress concentrations will require a larger support area, but still less than 1% of the available space.

Hoop Loads on the Mesh First Wall Due to X-Ray Ablation. The tensile hoop stress in a solid (not-mesh) cylindrical wall is

$$\sigma = (P_\tau/\delta)\,(Y/\rho)^{1/2} \qquad (2)$$

when the loading time (τ) is less than the wall period (~ 5 ms). For steel, the modulus (Y) is ~ 200 GPa, and the density (ρ) is 7860 kg/m^3. For a 100 MPa fatigue stress limit, Eq. 2 can be inverted to find the required wall thickness

$$\delta(m) = 5.04 \times 10^{-5}\, P(Pa)\, \tau(s). \qquad (3)$$

The impulse, P_τ, is the momentum (p) per unit area of the ablated material (from the inner surface) since $P = p/A_\tau$. Thus, the momentum of the ablated material is the key parameter. For a 200 m^2 mesh surface area,

$$\delta(m) = 2.52 \times 10^{-7}\, p\ (kg{\cdot}m/s). \qquad (4)$$

Ignoring stress concentrations, Eq. 4 is valid for a screen because the holes reduce both the momentum applied and the load bearing capacity. However, stress concentrations could require thicknesses several times thicker than predicted by Eq. 4. Conversely, if a significant portion of the mesh recoil momentum can be transferred to liquid on its outer surface (rear surface spall of the liquid), the required thickness will decrease.

For a 600 MJ target (ρR ~ 3 g/cm^2), the combined x-ray and debris yield is 192 MJ (32%). The x-rays arrive first. If the x-ray ablated material is dense enough, it will absorb the debris and thereby reduce the momentum transferred to the mesh. This mitigating effect is ignored here.

One simple model to calculate the recoil momentum is to ignore vaporization and just consider liquid ablation. Then,

$$p = mv = m\,\Gamma\,(E/m) / c = \Gamma E/c. \qquad (5)$$

For lithium, the Grüneisan parameter (Γ) = 1 and the sound speed (c) = 4500 m/s. For LiPb, Γ = 2 and c = 1800 m/s. Thus, for E = 192 MJ, p = 42,700 and 213,000 kg·m/s for lithium and LiPb, respectively. The required wall thicknesses are 1.1 and 5.4 cm for lithium and LiPb.

Consideration of vaporization is more complex. If it is assumed that all absorbed energy above the specific cohesive energy (e_{coh}) is kinetic (no random thermal motion, all atoms leave the surface in a perpendicular direction), then

$$p = (2mE)^{1/2} = [2m^2(\frac{E}{m} - e_{coh})]^{1/2} . \quad (6)$$

The cohesive energy (from 500°C to vapor) is 21 MJ/kg for lithium, and 860 kJ/kg for lead (the lead value will be used for LiPb here). For ablation thicknesses of 1 μm and 10 μm, the maximum lithium momenta are 6070 and 18,250 kg•m/s, respectively; and the analagous lead momenta are 26,800 and 81,300 kg•m/s. Vaporization produces less momentum per unit of deposited energy because of the influence of the cohesive energy. For high ablation temperatures (where the cohesive energy is negligible and m is very small), the momentum generation is even less efficient because $P \sim \sqrt{E}$ rather than E.

The liquid ablation model provides an upper bound on the momentum generation. Since the debris energy is probably absorbed in decoupled (ablated) material, and since the leading edge of the exponential x-ray energy deposition profile generates momentum less efficiently, the model is conservative. A more thorough calculation including a detailed x-ray deposition profile indicates that, for lithium, the error is about a factor of 3. Thus, ignoring stress concentrations, 4 mm and 2 cm thick mesh walls will be needed for the lithium and LiPb versions of Pulse*Star.

SUMMARY

The Pulse*Star design study is about one-half complete. Key balance of plant issues have been resolved, leading to a cost effective reactor. Design of the first wall structure is underway. If the design goals are met, Pulse*Star could fulfill fusion's promise of an inexhaustible, low cost, safe, and environmentally clean energy source.

REFERENCES

1. J. A. BLINK and N. J. HOFFMAN, "Tritium Control and Activation in the Pulse*Star Reactor", Proceedings 10th IEEE Symposium on Fusion Engineering, Philadelphia, PA (Dec. 1983).

2. K. A. MURRAY, et al, "A Comparison of Li and 83Pb-17Li Primary Coolant and designs for the Pulse*Star Inertial Confinement Fusion Rector", this meeting.

3. N. J. HOFFMAN, et al, "Polonium Aspects Associated with the use of Lead-Lithium Blankets in Fusion Applications", this meeting.

4. M. I. BASKES, Sandia National Laboratory, Livermore, private communication, Jan. 1985.

5. T. BARTEL, Nucl. Eng. Dept., U. of Wisconsin, private communication, August 1984.