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**PULSE*STAR ICF REACTOR - HEAT TRANSFER
LOOP AND BALANCE OF
PLANT CONSIDERATIONS**

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Lawrence
Livermore
National
Laboratory

PULSE*STAR

INERTIAL CONFINEMENT FUSION REACTOR

HEAT TRANSFER LOOP AND BALANCE OF

PLANT CONSIDERATIONS

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Energy Technology Engineering Center
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ABSTRACT

A conceptual heat transfer loop and balance of plant design for the Pulse*Star Inertial Confinement Fusion Reactor¹ has been investigated and results are presented. The Pulse*Star reaction vessel, a perforated steel bell jar approximately 11 m in diameter, is immersed in $\text{Li}_{17}\text{Pb}_{83}$ coolant which flows through the perforations and forms a 1.5 m thick plenum of droplets around an 8 m diameter inner chamber. The reactor and associated pumps, piping, and steam generators are contained within a 17 m diameter pool of $\text{Li}_{17}\text{Pb}_{83}$ coolant to minimize structural requirements and occupied space, resulting in reduced cost.

Four parallel heat transfer loops with flow rates of $5.5 \text{ m}^3/\text{s}$ each are necessary to transfer 3300 MWt of power. Liquid metal is pumped to the top of the pool by four pumps where it flows downward through eight vertical steam generators. Double-walled tubes are used in the steam generators to assure tritium containment without intermediate heat transfer loops. Each pump is a mixed flow type and has a required NPSH of 3.4 m, a speed of 278 rpm, and an impeller diameter of 1.2 m.

The steam generator design was optimized by finding the most cost-effective combination of heat exchanger area and pumping power. The design minimizes the total cost (heat exchanger area plus pumping) for the plant lifetime. The power required for the pumps is 36 MWe. Each steam generator is 12 m high and 1.6 m in diameter, with 2360 tubes. The steam generators and pumps fit easily in the pool between the reactor chamber and the pool wall.

Power balance calculations based on an improved electrical conversion efficiency revealed a net electrical output of 1260 MWe to the bus bar and a resulting net efficiency of 39%. Suggested balance-of-plant layouts are also presented.

I. INTRODUCTION

Pulse*Star is an inertial fusion reactor concept proposed by Lawrence Livermore National Laboratory¹ in which the reaction chamber and heat transfer system are contained within a pool of liquid $\text{Li}_{17}\text{Pb}_{83}$ coolant. $\text{Li}_{17}\text{Pb}_{83}$ was chosen rather than pure Li because the mixture does not react violently with water, air, or concrete. The coolant surrounds the reaction chamber, a bell jar approximately 11 m in outer diameter, and flows through the porous chamber wall to form a 1.5-meter-thick plenum of droplets (50 void percent) around an 8-meter-diameter inner chamber. The plenum of droplets is confined by an inner screen, which it wets. The wet screen absorbs the x-rays and debris from the fusion target while the droplets in the plenum absorb most of the fusion neutrons. The $\text{Li}_{17}\text{Pb}_{83}$ also serves as the heat transfer medium between the reactor and steam generator. The interior of the reactor chamber is a vacuum to allow laser beam propagation. The bell jar, pumps, piping, and steam generators are contained within one large coolant pool (approximately 17 m in diameter) so that structural requirements and space taken up by the system are minimized.

The high density of the $\text{Li}_{17}\text{Pb}_{83}$ liquid creates severe structural support problems for piping and components containing the $\text{Li}_{17}\text{Pb}_{83}$. As an example, 0.6-m- (24-in.)-diameter pipe containing $\text{Li}_{17}\text{Pb}_{83}$ weighs about 3000 kg (6600 lb) per meter of length. The pool design eliminates much of the structural support problem by immersing the pipe and components in $\text{Li}_{18}\text{Pb}_{83}$, thus buoying them up. Another problem faced by power plant designers is the allowance for thermal expansion of piping and components. This is usually solved by adding expansion loops to the piping to make it more flexible. The pool concept allows slip joints to be used to absorb the thermal expansion. This is possible because a small amount of leakage from the hot piping to the cooler pool can be tolerated. Proper design of the slip joints minimizes that leakage.

The reactor is designed to produce 3300 MWt of energy with an approximate 1300-MWe net electrical plant output.

The objectives of this study are to provide conceptual configurations for the pumps and steam generators in the pool while minimizing capital costs and pumping power. The use of double-walled tubes in the steam generator eliminates the necessity of intermediate heat transfer loops, which reduces costs. Other objectives of this study are to suggest a layout of the balance of the power plant and to provide the plant overall power balance.

II. HEAT TRANSFER LOOP - CONCEPTUAL CONFIGURATIONS

A. HEAT TRANSFER PROPERTIES OF $\text{Li}_{17}\text{Pb}_{83}$

Although the heat transfer properties for pure lithium and pure lead are well documented, the properties of lead-lithium solutions have not been thoroughly investigated. Hoffman et al² published the densities of lead-lithium solutions at 500°C and at the liquidus temperature. That reference also provided the electrical conductivity of LiPb solutions as a function of the Pb-to-Li concentration ratio. This was used to calculate the thermal conductivity of $\text{Li}_{17}\text{Pb}_{83}$ by scaling the conductivity function based on the known end point thermal conductivities of pure Li and Pb. Because there are no references for viscosity or heat capacity, the average of the parameters for lithium and lead were used. The heat capacity of a solution usually varies with the weight of the solution, so a weighted average of the two values was used. The viscosity of a solution is usually related to the behavior of the individual atoms in the solution, so the atomic average of the viscosities of lithium and lead was used to determine the viscosity of $\text{Li}_{17}\text{Pb}_{83}$. A summary of values of the heat transfer properties used in this study is given in Table 1.

Table 1. Heat Transfer Properties of $\text{Li}_{17}\text{Pb}_{83}$ at 500°C

Thermal conductivity	k	11.6 W/m°C	6.7 Btu/hr-ft°F
Density	ρ	9400 kg/m ³	587 lb/ft ³
Viscosity	μ	2.09×10^{-3} kg/m·s	1.4×10^{-3} lbm/ft-s
Heat capacity	Cp	0.161 kJ/kg°C	0.038 Btu/lbm°F

B. DESIGN PARAMETERS FOR THE HEAT TRANSFER LOOP

The heat transfer loop is designed to transfer 3300 MWt of energy to the steam generators. The hot leg and cold leg temperatures of the $\text{Li}_{17}\text{Pb}_{83}$ coolant have been determined by material strength criteria. The pumps and piping are of 2-1/4 Cr - 1 Mo steel, which has a (safe) upper material strength limit of 500°C (930°F). A lower temperature limit of 400°C (750°F) is dictated because the steel is in danger of radiation-induced embrittlement at temperatures below 350°C (660°F). The system ΔT , therefore, is 100°C (180°F). The melting point of $\text{Li}_{17}\text{Pb}_{83}$ is 235°C (455°F), well below the cold leg temperature.

In order to produce 3300 MWt from a 100°C temperature difference, the flow rate through the heat exchanger system must be 22 m³/s (350,000 gpm). A division of the flow into four parallel heat transfer loops results in a flow rate of 5.5 m³/s (87,000 gpm) through each loop, which is a reasonable flow rate for a liquid metal pump. Because liquid lead-lithium has a high density, a low flow velocity through each loop is necessary to minimize the piping pressure loss component of the pumping power. A reasonably low flow velocity of 4.7 m/s (15.4 ft/s) is obtainable by using 1.2-m (48-in.-ID) piping. The calculated pressure loss through the pipe at the above velocity is approximately 0.01 meter of head for each meter of pipe length. Thus, the piping pressure loss is minimal.

Because the design involves 500°C $\text{Li}_{17}\text{Pb}_{83}$ traveling within a pipe immersed in 400°C $\text{Li}_{17}\text{Pb}_{83}$, there was some concern about heat loss through the pipe into the cooler medium. A calculation showed that in an uninsulated pipe, the hot fluid would cool about 2.3°C (4.1°F) between the reaction chamber outlet and the heat exchanger inlet, a total loss of about 76 MWt. To reduce the heat loss, 1 cm (0.4 in.) of insulation is sandwiched between two concentric pipe walls that transport the hot fluid. Calcium silicate has been used before as an insulator in liquid metal systems and has a k value of 0.11 W/m°C (0.061 Btu/ft°F). The energy loss through the insulated pipe is reduced to only 0.3 MWt.

C. PUMP SELECTION

A pump is required in each of the four heat transfer loops to force the $\text{Li}_{17}\text{Pb}_{83}$ liquid through the steam generators and maintain the pool level above the evacuated reaction chamber. The high density and low heat capacity of the $\text{Li}_{17}\text{Pb}_{83}$ liquid causes the pumping power to be a significant portion of the in-plant consumed power. This emphasizes the importance of the pump design in the overall design of the plant. The pump characteristics and dimensions are summarized in Table 2 and discussed in detail below.

Table 2. Primary Pump Parameters

Number of pumps	4	
Flow per pump	$5.5 \text{ m}^3/\text{s}$	87,000 gpm
Developed head	14.0 m	46 ft
Developed pressure	1.3 MPa	190 psi
NPSH available	4 m	13 ft
NPSH required	3.4 m	11 ft
Impeller diameter	1.2 m	48 in.
Pump speed	278 rpm	
Net fluid power per pump	7.1 MW	9,500 hp
Electric power per pump	8.9 MWe	11,900 hp
Pump heat absorbed by liquid (includes fluid power)	8.4 MW_t	11,300 hp

The flow rate of each pump was set by the required flow in each of the four heat transfer loops at $5.5 \text{ m}^3/\text{s}$ (87,000 gpm). The required pressure rise generated by the pump is set almost exclusively by the height of the pool surface over the surface of the catch basin below the reaction chamber, 12.5 m (41 ft). The designs of the piping system and the steam generators result in small pressure losses and a combined contribution of only 1.5 m (5 ft) of head.

No choices existed in determining the location of the pumps. They had to be located below the elevation of the reaction chamber outlet with gravity inducing the flow from the chamber outlet to pump suction. The distance below the chamber outlet was set by the liquid height requirements for pump NPSH (net positive suction head). Access requirements for maintenance dictated that the pumps not be placed directly beneath the reaction chamber, but around its periphery.

A choice did exist as to whether to use an electromagnetic or a mechanical pump. Both type pumps are commonly used in liquid metal systems, and each has advantages and disadvantages. For this application, however, the mechanical pump is the proper choice. The high electrical resistivity of the $\text{Li}_{17}\text{Pb}_{83}$ liquid (compared to pure lithium) makes electromagnetic pumping very inefficient. An additional drawback of an electromagnetic pump in this application is the need to provide cooling to the electric coils of the pump. Flowing gas is normally used for such cooling. Here, that would require ducting from the top of the pool to the pump and back. The mechanical pump can be expected to operate with an efficiency of 80%. The drive system can be located above the pool with power transmitted down a shaft to the impeller.

The head / flow characteristics needed for the Pulse*Star pumps are somewhat unusual among liquid metal pumps which have been built. The pumps have unusually low-head, high-flow requirements. Figure 1 shows the head / flow characteristics of a number of the liquid metal pumps which have been built and the ranges to be expected from different types of mechanical pumps.³ As shown, the Pulse*Star pump characteristics put them in the range of mixed flow pumps.

The terms Axial Flow, Mixed Flow, and Radial Flow refer to the direction of flow through the pump impeller. The axial flow impeller is similar to a boat propeller with the liquid flow passing through the impeller in parallel with the pump shaft. The radial flow impeller causes the flow to leave the impeller in a direction perpendicular to the pump shaft. Mixed flow impellers have flow behavior between the axial and radial designs.

Figure 1
Classification of Existing Mechanical Pumps
by Hydraulic Characteristics

Pump Identity	Year (Approx.)	Where Used	Fluid	Temp. Deg.C
PKA	1950	Oak Ridge National Laboratory	Molten Salt	800
LASL	1956	Los Alamos Scientific Laboratory	Na	600
LCRE	1963	Connecticut Aircraft Nuclear Engineering Laboratory	Li	600
CANEL	1960	Connecticut Aircraft Nuclear Engineering Laboratory	NaK	600 and 700
APDA PRI	1965	Enrico Fermi Fast Breeder Reactor	Na	540
APDA SEC	1965	Enrico Fermi Fast Breeder Reactor	Na	510
HNPf	1962	Hallam Nuclear Power Facility	Na	510
EBR-II	1960	Experimental Breeder Reactor	Na	425
SRE-PEP	1968	Sodium Reactor Experiment	Na	650
SCTI	1962	Energy Technology Engineering Center	Na	650

While not normally used to pump liquid metals, the mixed-flow-type pump is commonly used in other applications where low-head, high-flow characteristics are needed. Figure 2 shows a mixed flow pump used for pumping water. The configuration of the pump is very similar to that planned for the Pulse*Star pump. The impellers are staged in series with the pump shaft passing down the center of the discharge pipe. In Pulse*Star, the discharge piping is topped with a tee where the flow is split to go to the two steam generators per heat transfer loop. The drive system is located above the pool with the shaft passing through the pool closure assembly.

Figure 2. Two-Stage Mixed Flow Pump

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Some basic pump design equations were used to establish further design characteristics. To make sure that the pumps would fit conveniently around the periphery of the reaction vessel, the impeller diameter was set at 1.2 m (48 in.), the same size as the piping. The pump outside diameter will then be 1.8 m (6 ft). Work on low NPSH pumps for liquid metal applications has generated a guideline that the NPSH available should be greater than three times the dynamic head at the impeller entrance. With a flow velocity of 4.7 m/s, this consideration produced a required NPSH of 3.4 m (11 ft). To assure an adequate design margin to prevent pump cavitation, an NPSH of 4 m (13 ft) was designed into the plant.

The suction specific speed (S_s) for a low NPSH impeller can be up to 20,000 (English units), though 12,000 is more reasonable. It is defined as

$$S_s = N(\text{rpm}) V(\text{gpm})^{1/2} / \text{NPSH}(\text{ft})^{3/4}. \quad (1)$$

A suction specific speed of 20,000 can be achieved by using sharp, thin impeller blades. Even though the pump has a low head, the developed pressure is still high, 1.3 MPa (190 psi) because of the high $\text{Li}_{17}\text{Pb}_{83}$ density. Thin blade sections might be damaged by the pressure differentials; hence, a suction specific speed of 12,000 was selected and used to calculate the pump speed, 278 rpm.

The specific speed (N_s) for a pump is given by the equation

$$N_s = N(\text{rpm}) V(\text{gpm})^{1/2} / H^{3/4} \quad (2)$$

where H is the developed head (feet). A mixed flow impeller should have a specific speed of about 5,000 to 8,000 (English units).⁴ Table 3 gives the specific speed value for 1, 2 and 3 impellers. Two impellers will be used because they produce a specific speed in the recommended range. It is possible that detailed pump design and optimization might point to different designs for each impeller.

Table 3. Specific Speed Values for Different
Impeller Quantities

<u>No. of Impellers</u>	<u>Specific Speed</u>
1	4,600
2	7,800
3	10,500

The electric power required by the pump (in watts) is

$$\text{pump power} = \frac{V\rho gH}{\eta} \quad (3)$$

where V is the flow rate (m^3/s), ρ is the density (kg/m^3), H is the head (m), and η is the pump efficiency. The pumping power is 8.9 MWe for each pump based on an 80% efficiency and 1.4 m total head. The total pumping power for the $\text{Li}_{17}\text{Pb}_{83}$ recirculation system in the Pulse*Star plant is then 36 MWe, which is less than 3% of net plant output. Motors of the required power have been designed and built. The low pump speed, 278 rpm, is a negative factor since motor size grows when speed is reduced. A high rpm motor coupled with a gear speed reducer would be the most desirable arrangement for a compact design. In this design, an 1800 rpm motor is used in conjunction with a gear reducer to reduce pump speed to 278 rpm. The motor in this case is 2.9 m x 1.7 m x 1.7 m and weighs 10,000 kg. The gear reducer has approximately the same dimensions and weight.

D. STEAM GENERATOR DESIGN

The major requirement of the steam generator design is that the steam generators be located within the coolant pool, in close proximity to the reaction chamber. To minimize the pool dimensions, the steam generators should be compact. To minimize pumping power, the steam generator should also have a low pressure drop.

Double-walled tubes will be used in the steam generator to assure tritium containment without an intermediate heat transfer loop. Using double-walled tubes allows containment of the entire heat transfer loop within the pool. The tube design is a facsimile of the Westinghouse breeder reactor steam generator double-wall tube design⁵ (Figure 3). The tubes have an outer diameter of 2.06 cm and an inner diameter of 1.11 cm. Helium is the third fluid, located in four grooves between the inner and outer walls of the tubes.

Two different configurations were investigated for the steam generator design: an arrangement of horizontal crossflow steam generators located above the reactor at the top of the pool and an arrangement of vertical counterflow steam generators located around the pool periphery. Locating the steam generators at the bottom of the pool was not considered feasible because long steam and feedwater piping runs would be necessary, expansion loops would be needed, and maintenance, repair, and inspection would be much more difficult than if the steam generators were located at the top of the pool.

Figure 3. Double-Wall Tube Cross Section

The thermal energy extracted from the $\text{Li}_{17}\text{Pb}_{83}$ is used to generate steam in a conventional LMFBR steam cycle. The parameters for this cycle are given in Table 4. These are design conditions applicable to a commercial fusion power plant with liquid metal-type steam generators. The electrical conversion efficiency is approximately 39%. This efficiency could be made higher (up to 44%), but at the expense of higher heat exchanger capital cost. Optimization of the efficiency is discussed further in Section IV, Plant Power Balance. The heat transfer calculations in this report are based on the parameters in Table 4.

The total required heat transfer surface area is given by

$$A = Q/U\Delta T_{lm} \quad (4)$$

where Q is the total power requirement (3300 MWt), U is the overall heat transfer coefficient ($\text{W/m}^2\cdot\text{K}$), and ΔT_{lm} is the log mean temperature difference, given by the following equation:

$$\Delta T_{lm} = \frac{(T_{in, \text{LiPb}} - T_{out, \text{H}_2\text{O}}) - (T_{out, \text{LiPb}} - T_{in, \text{H}_2\text{O}})}{\ln ((T_{in, \text{LiPb}} - T_{out, \text{H}_2\text{O}}) / (T_{out, \text{LiPb}} - T_{in, \text{H}_2\text{O}}))} \quad (5)$$

The above equation is valid for single phase, completely countercurrent flow. It can be used for flow in which a change of phase occurs, as in this case, because the given tube side heat transfer coefficient takes into account the presence of both water and steam on the tube side. In the case of crossflow, the log mean temperature difference must be multiplied by a correction factor to obtain the appropriate mean temperature difference. For the temperatures used in this design, the crossflow correction factor is 0.87.⁶ The ΔT_{lm} for counterflow is 93°C (168°F) and for crossflow is 81°C (146°F).

The overall heat transfer coefficient, U , is related to the individual heat transfer coefficients by the following equation:

$$1/U = 1/h_s + A_o/h_t A_i + A_o/h_w A_{lm} \quad (6)$$

The average heat transfer coefficients through the tube walls (h_w) and on the tube (steam) side (h_t) have been measured by Westinghouse as 5.7×10^3 $W/m^2 \cdot K$ and 1.4×10^4 $W/m^2 \cdot K$, respectively.⁷ The shell (LiPb) side heat transfer coefficient (h_g) is dependent on tube spacing and configuration. A_o is the outside heat transfer surface area, A_i is the inside heat transfer surface area, and A_{lm} is the log mean area $(A_o - A_i) / (\ln(A_o / A_i))$.

Table 4. Pulse*Star Steam Cycle Parameters

Li ₁₇ Pb ₈₃ Inlet Temperature	500°C	930°F
Li ₁₇ Pb ₈₃ Outlet Temperature	400°C	750°F
Feedwater Temperature	230°C	440°F
Steam Temperature	460°C	855°F
Pressure	15.8 MPa	2290 psia

The pressure drop through the steam generator is dependent on tube spacing and number of rows of tubes. Because both the heat transfer coefficient and pressure drop are dependent on tube spacing, the steam generator design can be optimized by finding the tube spacing that will give the most cost-effective combination of heat exchanger area and pumping power. As the tube spacing increases, flow resistance is reduced and pumping costs decrease. At the same time, the heat transfer coefficient is reduced, resulting in increased tube surface area and increased steam generator cost. This increase in surface area may also result in a larger required pool diameter or depth to contain the larger steam generators. The objective is to select a tube spacing that will minimize the total cost (pumping plus heat exchanger area) for the plant lifetime.

Economic parameters for the optimization of the steam generator are as follows: plant electrical costs are currently 3¢/KW_eh. If an 80% pump efficiency and 80% plant capacity factor are assumed, along with a plant life of 30 years and an economic rate of return of 12% per year, then the present value of the lifetime pump operating cost is approximately \$4.3 million per meter of head (see the Appendix for detailed calculations). The slight

dependence of the pump capital cost on pump head is negligible in this analysis. The capital cost of a steam generator is proportional to its heat exchange surface area. A double-wall steam generator is estimated to be approximately one-third more expensive than a single-wall steam generator. The Westinghouse Nuclear Components Division contracted in July 1982 to make ten Clinch River Breeder Reactor (CRBR) single-wall steam generators for \$34 million. This results in a double-wall steam generator cost of approximately \$6,000 per square meter (see Appendix). There may be other factors involved in determining the cost of horizontal and vertical steam generators, but in this design only the tube cost is considered, and thus the costs per length of tubing are equal for both horizontal and vertical steam generators.

1. Crossflow Steam Generator Design

In this design, four horizontal crossflow heat exchangers are situated above the bell jar. The pumps deposit the liquid metal on a free surface above the horizontal steam generator pipes via a manifold and the $\text{Li}_{17}\text{Pb}_{83}$ flows downward through the steam generator to the bell jar area. A two-pass U-tube configuration is used to reduce the number of tubesheet welds. A schematic of the crossflow steam generator is given in Figure 4.

A cross-section of the pool showing the horizontal steam generators is given in Figure 5. A pool diameter of 17 m was selected in order to give adequate space between the reactor and the pool edge to accommodate the pumps. Four steam generators can have a maximum cross-sectional area of 5 m x 7.5 m to fit within the pool. Approximately 1.5 m is needed for the end cap and U-tube bends on each steam generator; thus the crossflow area for each is 5 m x 6 m. The depth of the steam generator will depend on the number of tubes needed which in turn depends on the shell side heat transfer coefficient.

The heat transfer coefficient for the shell side of the crossflow heat exchanger was calculated from a special equation for 90° crossflow of liquid metals through staggered tube banks:⁸

$$h_s = \frac{k}{D} \sqrt{\frac{\phi_1}{D}} \left(1 - \frac{D}{P}\right) \left[6.19 + 0.2665 (Pe)^{0.653}\right] \quad (7)$$

where k is the thermal conductivity of $Li_{17}Pb_{83}$, D is the tube diameter, P is the tube pitch, and values of ϕ_1/D can be found in Figure 6. The Peclet number (Pe) is defined as:

$$(Pe) = (Dv\rho C_p/k) \quad (8)$$

where v is the crossflow velocity of liquid metal coolant based on the minimum flow area. Equation (7) assumes that the outer surfaces of the tubes are completely wetted by liquid metal. In actuality, $Li_{17}Pb_{83}$ may not wet the surfaces unless extreme measures are taken. If this non-wetting phenomenon occurs,

Figure 4. Crossflow Steam Generator

Figure 5. Cross-Section of Pool Showing Crossflow Steam Generator Configuration

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Figure 6. Theoretical Values of the Hydrodynamic Potential Drop for Equilateral Triangular Spacing

83-N29-97-16

it would result in a heat transfer coefficient approximately 50% lower than that calculated by the above equation and an overall heat transfer coefficient about 20-25% lower than that of a wetted-wall system. All calculations in this report assume complete wetting.

The equation for pressure drop (in head units) through the shell side of a crossflow, unbaffled heat exchanger is:⁹

$$\Delta P = (2f N_R v^2)/g \quad (9)$$

where the friction factor f is⁹:

$$f = [0.23 + (0.11)/(P/D - 1)^{1.08}] \cdot [D\rho v/\mu]^{-0.15} \quad (10)$$

In these equations, N_R is the number of rows of tubes, v is the coolant velocity, $g = 9.8 \text{ m/s}^2$, ρ is the density (9400 kg/m^3) and μ is the viscosity (0.00209 kg/m's for $\text{Pb}_{83}\text{Li}_{17}$ at 500°C).

The method of removing the components from the pool for maintenance was analyzed. It is desirable to have the pumps and steam generator attached to the underside of the pool lid so that all components can be lifted out and moved to the maintenance area at one time. The major constraint against this design is the heavy lift weights of the components. Approximate component weights are given in Table 5. The total lift weight including the pool lid is approximately 10^6 kg . Bridge cranes to lift this amount have been constructed, but the industry limit has typically been 450,000 - 550,000 kg (500-600 tons) due to stress at the lift points. At this limit, the lid with pumps and motors attached could be lifted first, and the heat exchangers removed in a second lift. It is desirable to remove the pumps along with the lid because it would prevent having to detach the motors from the pump shafts, which penetrate the lid.

Table 5. Lift Weights of Pool Components

<u>Component</u>	<u>Weight (kg)</u>
Pool Lid (based on 0.25 m thickness)	450,000
Steam Generators (4)	475,000
Pump Shafts (4)	50,000
Pump Motors (4)	<u>40,000</u>
	1,015,000 kg (1100 tons)

A cross-section of the lid is shown in Figure 7. The figure shows the pump motor locations and lift points. The pump motor and gear reducer are located directly above the pump shaft on the pool lid rather than to the side to avoid the added expense of a horizontal drive train. If removed to a location off the lid, no weight savings would result because the drive train would have approximately the same weight as the motor and reducer. The motor is installed on top of the gear reducer rather than beside it because a right-angle gear drive is more expensive than a straight drive. The heat exchanger inlet and outlet piping is located on the side of the pool and does not penetrate the lid.

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The results of heat transfer analyses using different tube spacings are given in Table 6. The pressure loss is calculated from equation (9). The heat transfer surface area was calculated from equation (4) using an overall U value calculated from equations (6) and (7). The number of tubes is found by dividing the total surface area by the exterior surface area of one tube ($= 0.39 \text{ m}^2$ for a 6.0 m long tube). The heat exchanger height is found by the following equation:

$$\text{height} = \frac{\text{no. of tubes}}{\text{no. of tubes per row}} \frac{\sqrt{3}}{2} P \quad (11)$$

where

$$\text{no. of tubes per row} = \frac{\text{heat exchanger width}}{P} \quad (12)$$

The factor $\sqrt{3}/2$ is present in equation (11) because the tubes have an equilateral triangular spacing.

Table 6. Crossflow Steam Generator - Analysis Results
(Each of Four Steam Generators)

<u>P/D</u>	<u>Pressure Loss (m)</u>	<u>h_g (W/m²·K)</u>	<u>Heat Transfer Surface (m²)</u>	<u>Number of Tubes</u>	<u>Steam Generator Height (m)</u>
1.2	1.65	4293	4150	10600	1.1
1.5	0.32	3490	4240	10900	1.8
2.0	0.15	3143	4290	11000	3.3

Table 6 shows that the pressure loss decreases and the heat transfer surface area and steam generator height increase as P/D increases. The heat transfer surface area does not vary greatly with P/D, because heat transfer is dominated by tube side and tube wall coefficients. The steam generator cost and pumping power cost were calculated for each P/D value using previously discussed economic parameters and are plotted in Figure 8. The sum cost is also shown on the plot. A P/D value of 1.5 gives the lowest total cost. This is a heat exchanger with a height of 1.8 m and a tube spacing of 0.031 m.

Figure 8. P/D vs SG Capital Cost and Pump Operating Cost:
Crossflow and Counterflow Cases

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2. Countercurrent Steam Generator Design

In this design, eight vertical counterflow steam generators are located between the reactor shell and the pool wall. The $\text{Li}_{17}\text{Pb}_{83}$ is pumped to the top of the pool where the flow from each pump is split and travels downward through two steam generators. The feedwater is pumped to the bottom of the steam generators through a central conduit and flows upward. A schematic of the counterflow steam generator is given in Figure 9. Differential expansion of the tubes is accounted for in the design by attaching a slip fitting to the bottom feedwater tubesheet. The lead-lithium flows out in all directions into the surrounding pool.

Figure 9. Countercurrent Steam Generator

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The length of the tubes is 12 m, to correspond with the approximate height of the reactor chamber. The diameter of the heat exchanger depends on the optimum P/D selected for the design.

The heat transfer coefficient for the shell side of the countercurrent heat exchanger is calculated from a special equation for in-line flow of liquid metals through tube banks.⁸

$$h_s = k/D_e \left[6.65 + 3.126 (P/D) + 1.184 (P/D)^2 + 0.0155 (\psi Pe)^{0.86} \right] \quad (13)$$

where k = thermal conductivity, D_e is the equivalent shell side diameter given by

$$D_e = 4 (\text{flow area/wetted perimeter}) \quad (14)$$

and ψ is a diffusivity ratio, given by

$$\psi = 1 - \frac{1.82}{(\epsilon_m/\nu)^{1.4} Pr} \quad (15)$$

The Prandtl number (Pr) in equation (15) is equal to $C_p \mu/k$, and (ϵ_m/ν) is a function of the Reynolds number, as shown in Figure 10. As in the crossflow case, these equations assume completely wetted walls.

The equation for pressure drop (in head units) through the shell side of an unbaffled countercurrent heat exchanger is:

$$\Delta P = f (L/D_e) (v^2/2g) \quad (16)$$

where

$$f = 0.316/Re^{0.25} \quad (17)$$

This friction factor correlation is standard for turbulent flow in a pipe and is applicable to the shell side of the steam generator if D_e is used in the Reynolds number.

Figure 10. Maximum Values of (ϵ_m/ν) for Fully Developed Turbulent Flow Through Rod Bundles With Equilateral Triangular Spacing

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The results of a heat transfer analysis using several values of P/D are given in Table 7. The pressure loss is calculated from equation (16). The heat transfer surface area was calculated using equation (4) and the shell side heat transfer coefficient given by equation (13). The number of tubes is equal to the total surface area divided by the surface area of one tube (0.78 m^2 for a 12 m long tube). The approximate heat exchanger cross-sectional area (including tubes) is:

$$\text{Area} = (\text{no. of tubes}) \frac{\sqrt{3}}{2} P^2 \quad (18)$$

The tube geometry is illustrated in Figure 11.

Table 7. Countercurrent Steam Generator - Analysis Results
Each of Eight Steam Generators

<u>P/D</u>	<u>Pressure Loss (m)</u>	<u>hs (W/m²·K)</u>	<u>Heat Transfer Surface (m²)</u>	<u>Number of Tubes</u>	<u>Heat Exchanger Diameter (m)</u>
1.2	27.1	9110	1710	2200	1.22
1.5	1.48	3527	1840	2360	1.58
2.0	0.09	1467	2150	2760	2.28

Table 7 shows that the variation of P/D causes a larger variation in heat transfer surface area and pressure loss than in the crossflow case. This is because the shell side heat transfer coefficient depends on D_e , which varies significantly with P/D. As in the crossflow case, the heat transfer surface area increases and the pressure drop decreases with increasing P/D value. The results of an economic evaluation, using the same cost factors as in the crossflow case, are given in Figure 8. A P/D of 1.5 results in the lowest total capital and operating cost. This corresponds to a steam generator diameter of 1.6 m, which fits easily in the pool between the reaction chamber and the pool wall. A plan and elevation view of the $Li_{17}Pb_3$ pool with the eight vertical steam generators is shown in Figure 12.

Figure 11. Countercurrent Steam Generator Cross-Sectional Tube Geometry

AREA OF ONE HEXAGON

$$= (6)(1/2)(P/\sqrt{3})(P/2) \\ = \sqrt{3}P^2/2$$

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Figure 12. Plan and Elevation View of Pulse*Star Pool

3. Comparison of Crossflow to Counterflow Case

The major design features of the crossflow and the counterflow steam generators are listed in Table 8. The values correspond to the optimum design configuration in each case. The crossflow heat exchanger configuration requires 15% more heat transfer area than the countercurrent case. The difference is due mainly to the log mean temperature difference correction factor of 0.87 used in the crossflow case.

Table 8. Comparison of Crossflow and Counterflow
Steam Generator Configurations

	<u>Crossflow</u>	<u>Counterflow</u>
Number of Steam Generators	4	8
Total HX Area	16,960 m ²	14,720 m ²
Li ₁₇ Pb ₈₃ Pool Height	20.5 m	17.5 m
Li ₁₇ Pb ₈₃ Pool Diameter	17 m	17 m
Total Required Pumping Power	40.1 MW	35.5 MW
Pressure Drop Through HX	0.3 m	1.5 m
Total Capital and Operating Cost	\$103.1M	\$94.6M
LiPb Volume in Pool	4090 m ³	3400 m ³

The pool height in a crossflow configuration must be 3 m higher than a countercurrent configuration in order to accommodate the horizontal steam generators above the reactor. The pool diameters are the same in both cases. The total required pumping power is slightly larger for the crossflow case even though the pressure drop through the crossflow steam generators is less than through the counterflow steam generators (0.3 m compared to 1.5 m), because the liquid must be pumped an additional 3 m above the reaction chamber to account for the presence of the horizontal heat exchangers. The total operating and capital cost (cost of heat exchanger plus pumping power) for the crossflow case is approximately 9% greater than the amount required in the counterflow case. Additional cost savings for the counterflow design will be realized by a reduced pool depth and a smaller Li₁₇Pb₈₃ volume.

From a reliability standpoint, there is no difference between horizontal and vertical configurations when liquid metal is the shell side fluid. A horizontal steam generator is more reliable only if two phase flow is present on the shell side. In that case, stress corrosion cracking at tubesheet welds occurs in a vertical steam generator as a result of evaporation of droplets and the subsequent concentration of mineral deposits. Horizontal steam generators do not have tubesheet welds in the two phase region and thus avoid weld failures. However, in the Pulse*Star design, the steam is contained inside the tubes, and stress corrosion cracking is not a problem in either the vertical or horizontal steam generator designs.

The above analysis indicates that the counterflow steam generators are the more economic choice, and they were selected for the Pulse*Star power plant design.

III. BALANCE OF PLANT CONSIDERATIONS

A schematic of a possible balance of plant layout is shown in Figure 13. The layout is designed to provide an efficient, compact arrangement of components around the liquid metal pool. The area of the plant outlined in heavy black on the schematic is the Class I containment area and includes all structures and components necessary for safe operation and shut-down in case of a plant emergency. All of these structures are designed to withstand or be protected from the effects of environmental conditions (earthquake, flood, or tornado). The $\text{Li}_{17}\text{Pb}_{83}$ pool and drain tanks are recessed below grade for structural support and radiological shielding. The laser beam ports are also below grade to be in line with the center of the reaction chamber. To avoid extensive excavation, all other areas of the plant are above ground. The turbine generator building is located next to the reactor to minimize steam runs. The control room is located adjacent to the reactor and the turbine generator to minimize the instrumentation and control wiring leading to the major plant systems and buildings. A large maintenance area is located adjacent to the reactor pool to facilitate removal and service of the pool components. Storage tanks for the lead-lithium are located below grade next to the chamber to provide short transport piping runs when the $\text{Li}_{17}\text{Pb}_{83}$ coolant is drained. Diesel generators that provide auxiliary power are located close to the control room to reduce cable routing. The target factory and vacuum pumping areas are located near the laser beam port inlets to the reactor.

The turbine generator building makes up the balance of the plant. The turbine consists of four cylinders, or stages; a high-pressure barrel-type cylinder, an intermediate-pressure cylinder, and two low-pressure cylinders, as in a 1000-MWe LMFBR plant design.

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Figure 13. Plant Layout - Pulse*Star Fusion Power Plant

The Pulse*Star plant building sizes are compared to a 1000 MWe LMFBR plant design¹⁰ in Table 8. The Pulse*Star plant is smaller than the LMFBR plant because the reactor building is more compact and no steam generator buildings are required. The total floor area of the Pulse*Star plant is approximately 11 m²/MWe (based on a 1300 MWe output) and an equivalent LMFBR plant is approximately 18 m²/MWe. In addition, much less of the Pulse*Star floor space is within an expensive Class I containment structure. Further reduction of the Pulse*Star plant floor area may be possible after a closer look at the target fabrication building.

A schematic of a power plant incorporating multiple fusion reactor chambers is shown in Figure 14. This type of plant could produce three times the electrical energy output as the previous plant design, but only one-third of the laser cost would be charged to each plant. The approximate building sizes for this plant are shown in Table 9. Floor space is saved because only one control room, one laser building, and one maintenance area are needed. The laser can be made very reliable by building one spare beam line for each ten beam lines and allowing on-line maintenance of the unused beam line on a rotating basis. The total floor area of this plant layout is approximately 7 m²/MWe, or approximately 40% of the area of an equivalent LMFBR.

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Figure 14. Plant Layout - Multiple $\text{Li}_{17}\text{Pb}_{83}$ Pools

Table 9. Comparison of Pulse*Star Floor Area to LMFBF Design

Building	Floor Area (m ²)	Floor Area (m ²)
	Pulse*Star	LMFBF
Reactor Building	230	2900
Control Building	400*	1600
Turbine Generator Building	5200	5200
Steam Generator Maintenance and Service Area	1600	2900
Auxiliary Power Room	350*	700
Vacuum Pumping	400	-
Laser Building	4200	-
Target Fabrication	600	-
Fuel Handling	-	1300
Intermediate Building	-	700
Steam Generator Buildings	-	3000
	13400 m ²	18300 m ²
Area/MWe	10.6	18.3

*Much less complex safety and control equipment needed.

Table 10. Multi-Reactor Pulse*Star Plant Floor Areas

Building	Floor Area (m ²)
Reactor Buildings	700
Control Building	600
Turbine Generator Buildings	15600
S.G. Maintenance and Service Area	1600
Auxiliary Power Room	350
Vacuum Pumping Area	1200
Laser Building	4200
Target Fabrication	1000
	25300 m ²
Area/MWe	5.7

IV. PLANT POWER BALANCE

The main steam system parameters selected for the Pulse*Star system are based on an LMFBR design, which delivers steam at 460°C (855°F) and 15.8 MPa (2290 psia). The electrical conversion efficiency of the system is approximately 39%. A schematic heat balance for this system is shown in Figure 15. The efficiency can be improved by (1) increasing the temperature and thus the amount of superheat exiting the steam generators, or (2) adding a reheat cycle. The first item will reduce the log mean temperature difference between the steam and the $\text{Li}_{17}\text{Pb}_{83}$ and will thus increase the required heat transfer surface area. This increases the capital cost of the heat exchangers. The reheat cycle will require additional heaters and thus a further increase in capital cost. A revised heat balance was made including both items and a reduction in condenser pressure from 2.5 in. Hg to 1 in. Hg. The resulting efficiency is 43%. The revised heat balance is shown in Figure 16.

An economic analysis must be done to determine the optimum design. If the Figure 16 steam cycle (43% efficiency) is used, the 8 steam generator diameters will increase from 1.6 m to 1.9 m and 8 reheaters with diameters of 0.4 m must be added. The total heat transfer surface area will increase from 14,700 m² to 21,500 m². The reheaters and steam generators can still be contained within the specified 17 m diameter pool. The pump flow will be split into four lines at the top of the pool and will flow in parallel through the reheaters and heat exchangers.

A plant power balance based on a 43% electrical conversion efficiency is shown on Figure 17. Laser system and fusion chamber parameters were provided by LLNL.¹¹ The 4.3-Hertz repetition rate was selected to match the initially specified 3300 MWt. The LLNL-specified repetition rate of 5 Hertz will produce a higher plant thermal and electrical output.

The in-plant recirculated power requirements are based on an 1100 MW_t LMFBR design and ratios to the plant gross thermal output, except for the laser system and $\text{Li}_{17}\text{Pb}_{83}$ primary pump. The thermal energy contribution from pump heating has been included. This adds approximately 34 MW_t to the plant and 0.5% to the net plant efficiency. The net plant efficiency of 39% is 20% higher than the HYLIFE net plant efficiency.

Figure 15. PulseStar[®] Steam Cycle Heat Balance

Figure 16. Pulse*Star High Efficiency Steam Cycle Heat Balance.

Figure 17

Pulse*Star Power Balance

$$\text{NET EFFICIENCY} = \frac{\text{NET ELECTRIC}}{(\text{FUSION POWER}) (\text{SYSTEM MULTIPLICATION FACTOR})}$$

LASER POWER = 6% OF GROSS ELECTRIC POWER

TOTAL RECIRC. POWER = 12% OF GROSS ELECTRIC POWER

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V. CONCLUSIONS

The pool concept for an inertial confinement fusion reactor, as described here, appears to be an attractive option. A compact configuration for steam generators and $\text{Li}_{17}\text{Pb}_{83}$ recirculation pumps has been proposed that fits well around the periphery of the reaction chamber. Conceptual designs of the pumps and steam generators are within the range of existing technology. The recirculated power is shared equally by the laser system and the balance of plant. The recirculating power is reasonable, the plant net efficiency is higher than previous designs, and the net output exceeds 1000 MWe. The high density of the $\text{Li}_{17}\text{Pb}_{83}$ fluid does not increase pumping power to unacceptable levels.

Significant uncertainty exists as to the behavior of the $\text{Li}_{17}\text{Pb}_{83}$ liquid in heat transfer and power plant environments. Further work is needed to investigate the assumptions made in this report so that more detailed design work can be done. Further effort will be made to investigate a Pulse* Star concept using pure lithium as the pool fluid. Plant designs using lithium can be made with greater engineering confidence and less difficult tritium containment systems, but with more extensive safety systems.

VI. NOMENCLATURE

(Expressed in English units when consistent to equations)

- A - total heat transfer surface area based on outside of tube, m^2
- A_i - inside heat transfer surface area, m^2
- A_{lm} - log mean heat transfer surface area, m^2
- A_o - outside heat transfer surface area, m^2
- C_p - heat capacity, $J/kg \cdot K$
- D - tube diameter, m
- D_e - equivalent diameter, $= 4$ (flow area/wetted perimeter), m
- f - friction factor, dimensionless
- g - acceleration due to earth's gravity, m/s^2
- h - heat transfer coefficient, $W/m^2 \cdot K$
- H - developed head, ft
- k - thermal conductivity, $W/m \cdot K$
- L - steam generator length, m
- N - pump rotation rate, rpm
- NPSH - suction head, ft
- N_R - number of rows of tubes across which shell fluid flows
- N_S - pump specific speed, English units
- ΔP - pressure drop, or head, kg/ms^2 or m
- P - center-to-center distance between two tubes, m
- Pe - Peclet number, $= D_v C_p / k$, dimensionless
- Pr - Prandtl number, $= C_p \mu / k$, dimensionless
- Q - heat transfer rate, MW
- Re - Reynolds number, $= D_v \rho / \mu$, dimensionless
- S_s - suction specific speed, English units
- T_{in} - temperature of fluid entering steam generator, K
- ΔT_{lm} - log mean temperature difference, K
- T_{out} - temperature of fluid leaving steam generator, K
- U - overall heat transfer coefficient, $W/m^2 \cdot K$
- v - average fluid velocity, m/s
- V - pump flow rate, gpm or m^3/s
- ϵ_m - eddy diffusivity of momentum transfer, m^2/s
- μ - viscosity, $kg/m \cdot s$

- ρ - density, kg/m^3
- Φ_1 - unit hydrodynamic potential at the rear stagnation point of a rod, m
- ν - kinematic viscosity, $= \mu/\rho$, m^2/s
- ψ - ratio of heat transfer eddy diffusivity to momentum transfer eddy diffusivity, dimensionless
- η - pump efficiency, dimensionless

VII. REFERENCES

1. Monsler, M. J., "Pulse*Star: A-Pool-Type Reactor for Inertial Fusion Electric Power," Fifth Topical Meeting on the Technology of Fusion Energy, Knoxville, Tennessee, April 1983.
2. Hoffman, Darnell, Blink, "Properties of Lead-Lithium Solutions," Fourth Topical Meeting on the Technology of Controlled Nuclear Fusion, October 1980.
3. O. J. Foust, Editor: Liquid Metals Handbook Sodium and NaK Supplement, Liquid Metal Engineering Center, 1967.
4. D. G. Shepherd, Principles of Turbomachinery, MacMillan Publishing Company, Inc., New York, 1956.
5. "Equipment Specification - Intermediate A Prototype Steam Generator," Westinghouse Electric Corporation Breeder Reactor Component Project, June 1980.
6. Perry and Chilton, Editors, Chemical Engineers' Handbook, Fifth Edition, p. 10-24.
7. R. Waszink, Westinghouse BRCP, Personal Communication, February 1983.
8. O. E. Dwyer, "Liquid Metal Heat Transfer," Liquid Metals Handbook, 1970.
9. Peters and Timmerhaus, Plant Design and Economics for Chemical Engineers, McGraw-Hill Book Company, New York, 1980, p. 654.
10. "Liquid Metal Fast Breeder Reactor Conceptual Plant Design 1000 MWe," Rockwell International and Burns and Roe, May 1977.
11. J. A. Blink, LLNL, Personal Communication, February 1983.

APPENDIX - COST CALCULATIONS FOR PUMPING POWER AND STEAM GENERATORS

Pump Power Calculations

Average cost of electricity: \$.03/kWh

Pump power per meter of head (watts) = $\rho(\text{kg/m}^3) V (\text{m}^3/\text{s}) g (\text{m/s}^2)$

$$\rho = 9400 \text{ kg/m}^3$$

$$V = 22 \text{ m}^3/\text{s}$$

$$g = 9.81 \text{ m/s}^2$$

Power = 2.03 MW hydraulic

$$\begin{aligned} \text{Energy used per year} &= \frac{2.03 \text{ MW}_{\text{hydr}} (0.8 \text{ yr.op./yr})(24 \text{ hr/day})(365 \text{ day/yr})}{0.8 \text{ MW}_{\text{hydr}}/\text{MWe}} \\ &= 1.78 \times 10^7 \text{ kWh/yr} \end{aligned}$$

$$\text{Cost per year} = (1.78 \times 10^7 \text{ kWh/yr}) (\$0.03/\text{kWh}) = \$534,000$$

Present value factor of an annual cost (using 12% rate of return):

$$\frac{1 - (1 + i)^{-n}}{i} = \frac{1 - (1 + .12)^{-30}}{0.12} = 8.06$$

$$\text{Present value of pumping cost: } (\$534,000)(8.06) = \underline{\$4.30 \text{ million}}$$

m of head

Steam Generator Cost Estimation

Reference: Nuclear News, August 1982, p. 68:

Westinghouse to make 10 steam generators for \$34 million.

Each steam generator contains 757 tubes, 19.81 m long, 1.59 cm OD.

SA each steam generator $\approx (19.81 \text{ m}) \pi (.0159)(757) = 750 \text{ m}^2$

$$\frac{\$34 \text{ million}}{(10 \text{ s.g.'s})(750 \text{ m}^2)} = \$4500/\text{m}^2 \text{ of tube surface}$$

Double-walled tube more expensive, use 1.33 factor

$$(4500) (1.33) = \$6000/\text{m}^2 \text{ double-walled surface}$$

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