Synergistic Use of Liquid Lithium as
- Self-protecting First Wall
- Tritium Breeder, and
- LMMHD Electric Power Producer

Concepts
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<u>TWO NEW IDEAS FOR FUSION-RELATED POWER-EXTRACTION TECHNOLOGIES</u>

MOTIVATION: IMPROVED ECONOMICS FOR FUSION POWER

IDEA (1):
ELECTROMAGNETICALLY CONFINED LIQUID LITHIUM FIRST WALL & BREEDING BLANKET

IDEA 2):
INTEGRATED LMMHD ELECTRICAL POWER GENERATION

NOTE:
Both of these ideas rely onthe high electrical conductivity of liquid lithium. Neither could work properly if the liquid lithium were replaced by an alternative nonconductive lithium-bearing liquid such as "FLiBe".

BACKGROUND for (1): To extract all of the DT fusion power and achieve tritium breeding self-sufficiency, the thickness of a natural lithium blanket must be approximately one meter.

IDEA (1) : Confine a thick, flowing liquid lithium layer by electromagnetic and contact forces so as to almost completely enclose a toroidal magnetically confined plasma, thus forming a renewable <u>liquid lithium first wall</u> capable of high surface heat flux operation, neutron thermal power extraction, and tritium breeding.

BENEFITS of (1)

[Also see R.W. Moir "Liquid First Walls for Magnetic Fusion Energy Configurations", NUCLEAR FUSION, Vol.37, No.4 (1997)]

1)THE USE OF A FLOWING THICK LIQUID LITHIUM WALL ADJACENT TO THE PLASMA REDUCES NEUTRON DAMAGE ISSUES, INCLUDING THE NEED TO DEVELOP NOVEL MATERIALS RESISTANT TO 14 MEV NEUTRONS, and THE NEED FOR AN OPERATING FUSION POWER PLANT TO REGULARLY REPLACE PLASMA-FACING COMPONENTS. LIQUID LITHIUM HAS NO CRYSTALLINE STRUCTURE, AND SO CANNOT ITSELF BE DAMAGED BY HIGH ENERGY FUSION NEUTRON BOMBARDMENT, NO MATTER HOW INTENSE. THE LAYER OF LIQUID LITHIUM ALSO PROTECTS SOLID OBJECTS BEHIND IT BY ACTING AS A MODERATOR, SLOWING FUSION NEUTRONS TRANSITING THROUGH IT TO BENIGN ENERGY LEVELS BEFORE REACHING SOLID MATERIAL. THUS, THIS CONCEPT IMPLIES THAT EXOTIC NEW MATERIALS RESISTANT TO HIGH ENERGY NEUTRON BOMBARDMENT NEED NOT BE DEVELOPED OR USED.

2) BY PROVIDING A SELF-RENEWING FIRST WALL SURFACE MADE OF LIQUID (WHICH CAN NEITHER BE PERMANENTLY BROKEN NOR ERODED) THIS ENHANCES FUSION POWER PLANT ROBUSTNESS AGAINST PLASMA DISRUPTION EQUIPMENT DAMAGE.

3)THE MOVING LIQUID LITHIUM SURFACE ALLOWS HIGHER HEAT FLUX DENSITIES ON PLASMA-FACING SURFACES THAN STATIONARY SOLID SURFACES; THIS ECONOMICALLY PERMITS HIGHER PLANT POWER AT SMALLER PLANT SIZE.

4) BY ELIMINATING PLASMA-FACING SOLID SURFACES WHICH WOULD UNAVOIDABLY BECOME CONTAMINATED WITH TRITIUM, THIS MAY REDUCE THE MINIMUM TRITIUM INVENTORY AND THUS THE ASSOCIATED BIOHAZARD OF A DT FUSION POWER PLANT. MOST SURFACES WHICH COULD CONCEIVABLY BECOME CONTAMINATED BY TRITIUM ARE CONTINUALLY SWEPT BY FLOWING LIQUID LITHIUM.

5) BY PROVIDING THE CAPABILITY FOR THE BLANKET TO BE EFFORTLESSLY REMOVED FROM THE CHAMBER DURING FUSION PLASMA INITIATION AND THEN REPLENISHED FOR IGNITED OPERATIONS, THIS IDEA MAY SIMPLIFY THE DESIGN OF AUXILIARY PLASMA HEATING SYSTEMS NEEDED TO REACH IGNITION.

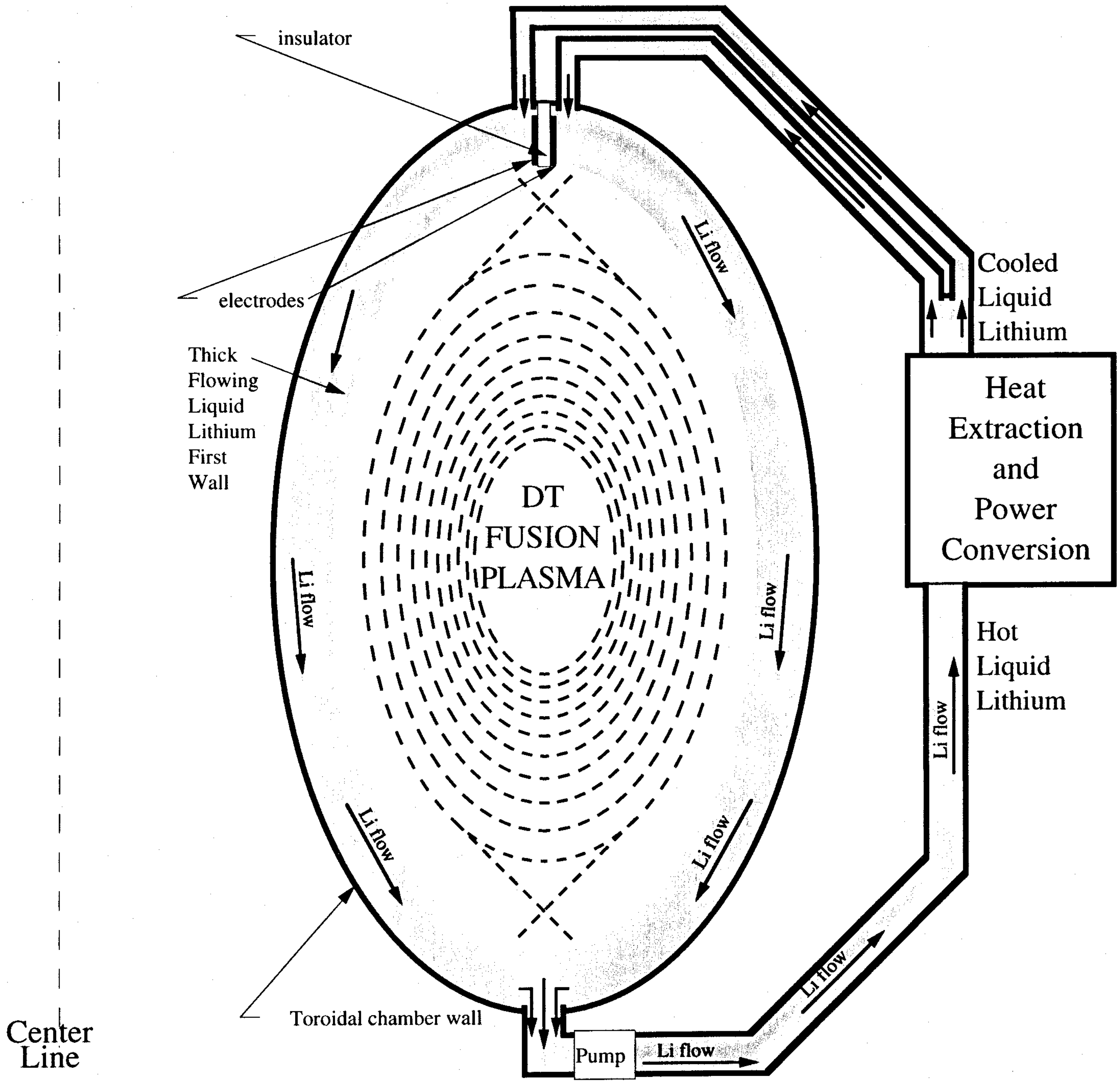
(1) Liquid Walls Confinement

- Analogous to an extra TF coil winding turn (made of flowing liquid lithium)
- **TWO AXISYMMETRIC STREAMS OF LIQUID LITHIUM ARE CONTINUOUSLY INJECTED INTO THE TOP OF A TOROIDAL CHAMBER WHICH CONTAINS A MAGNETICALLY CONFINED DT PLASMA UNDERGOING THERMONUCLEAR FUSION. POLOIDAL ELECTRICAL CURRENTS ARE DELIBERATELY DRIVEN IN OPPOSITE DIRECTIONS IN THE TWO LIQUID LITHIUM STREAMS, I.E., IN THE SAME DIRECTION FOR BOTH STREAMS AS THE CURRENT IN THE NEARBY TOROIDAL FIELD COILS WHICH ENCLOSE AND LINK THE TOROIDAL CHAMBER. THIS RESULTS IN ELECTROMAGNETIC "J X B" FORCES WHICH PUSH THE LIQUID LITHIUM OF BOTH STREAMS AGAINST THE CHAMBER WALLS AND THUS HOLD IT AWAY FROM THE PLASMA. THE OUTER STREAM FORMS THE LIQUID LITHIUM FIRST WALL "OUTBOARD" FROM THE PLASMA (I.E., AT LARGER MAJOR RADII) AND THE INNER STREAM FORMS THE LIQUID LITHIUM FIRST WALL "INBOARD" FROM THE PLASMA. UNDER THE COMBINED INFLUENCE OF GRAVITY AND ELECTROMAGNETIC FORCES, THE TWO STREAMS MOVE ALONG THE WALLS TO THE BOTTOM OF THE CHAMBER WHERE THEY EXIT THROUGH APERTURES PROVIDED FOR THAT PURPOSE.**

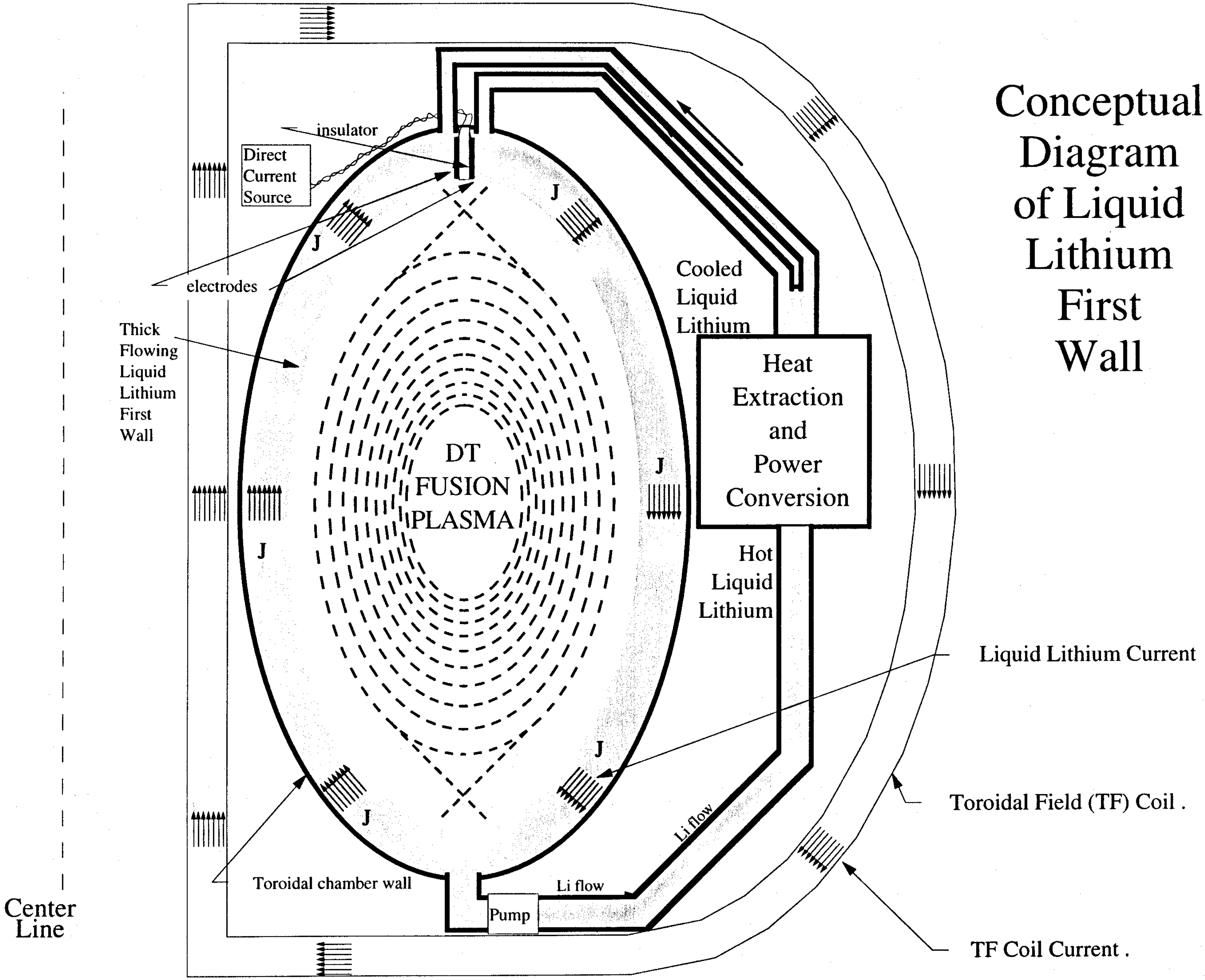
•THE TWO STREAMS ARE ELECTRICALLY SEPARATED FROM EACH OTHER AT THE TOP OF THE TOROIDAL CHAMBER VIA A HIGH ELECTRICAL RESISTANCE "INSULATING" STRUCTURE. ELECTRODES TOUCHING THE LIQUID LITHIUM STREAMS ON THE TWO SIDES OF THIS INSULATOR ARE ELECTRICALLY DRIVEN FROM AN EXTERNAL DIRECT-CURRENT POWER SOURCE IN ORDER TO PRODUCE THE LITHIUM-CONFINING POLOIDAL CURRENTS.

- FEATURES
  - -FLOW PATH andCURRENT FOLLOW FLUX SURFACE
  - -OPEN SURFACE is INSULATING
  - -No Toroidal Component in **V**, in **V X B**, in **E**, in **J**, or in **J X B**
  - -**J X B** is perpendicular to **V**, towards nearby vessel wall

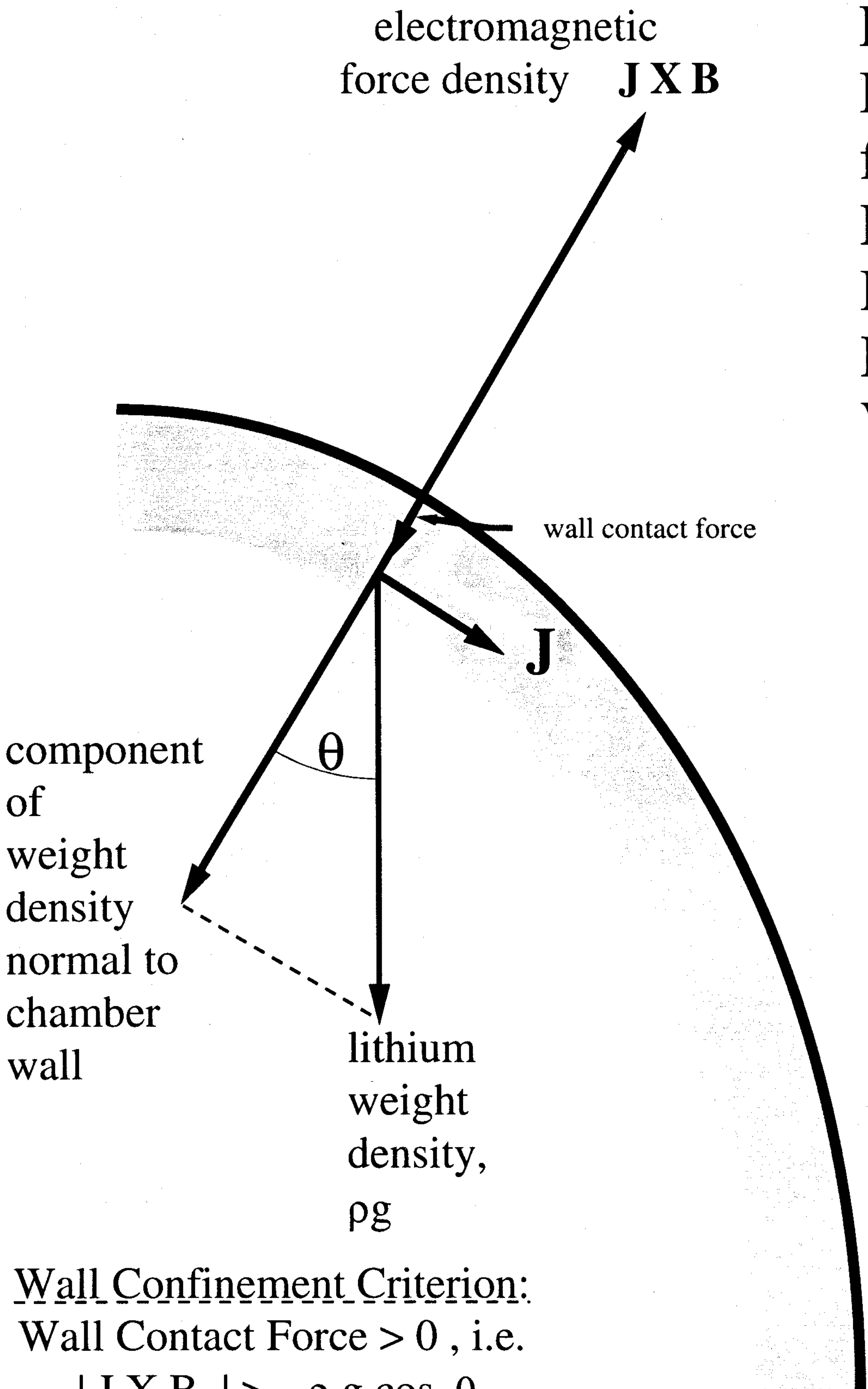
System Flow Diagram for Liquid Lithium First Wall



Conceptual Diagram of Liquid Lithium First Wall



Force Diagram for Liquid Lithium First Wall



<u>Wall Confinement Criterion:</u>

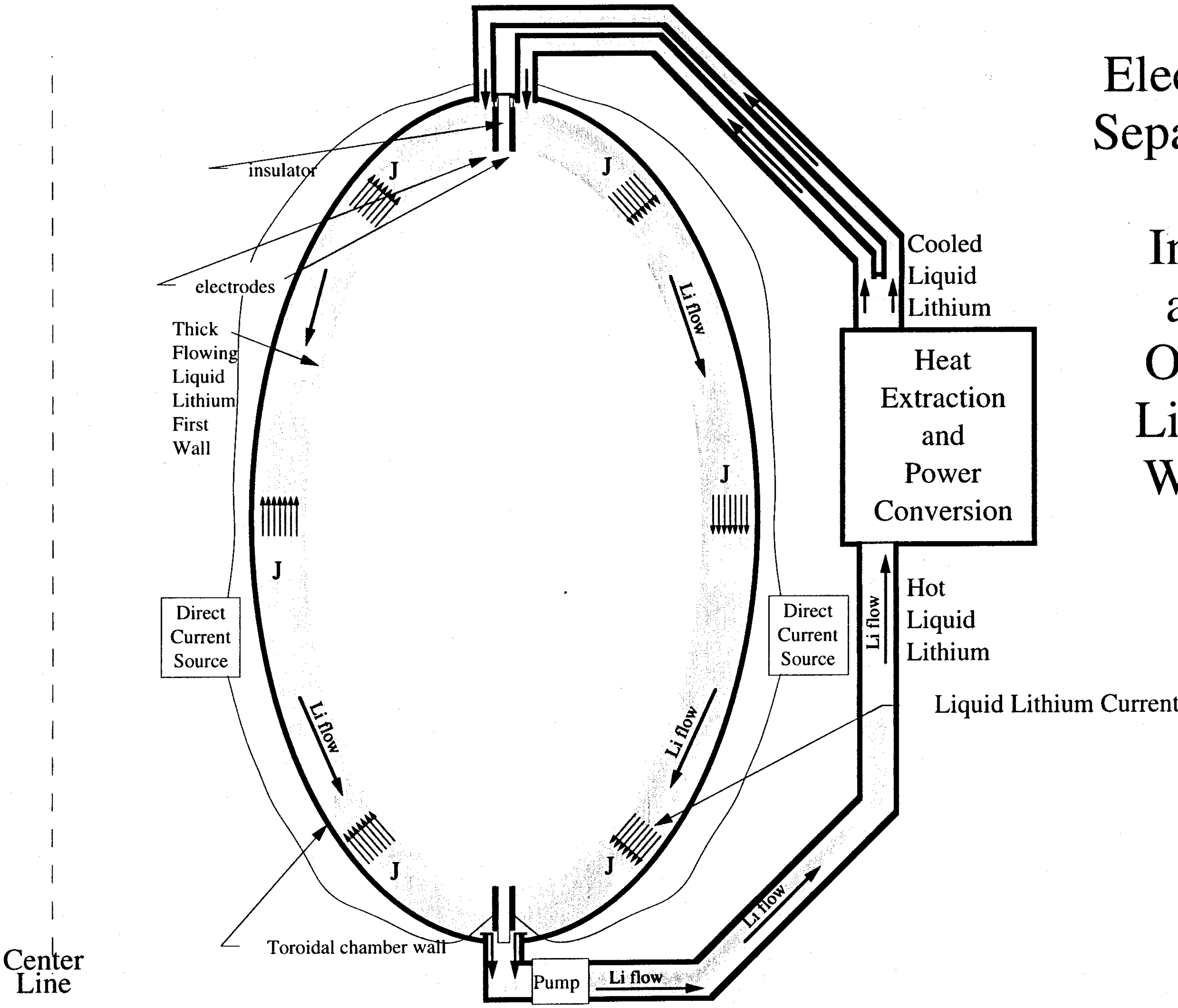
Wall Contact Force > 0 , i.e.

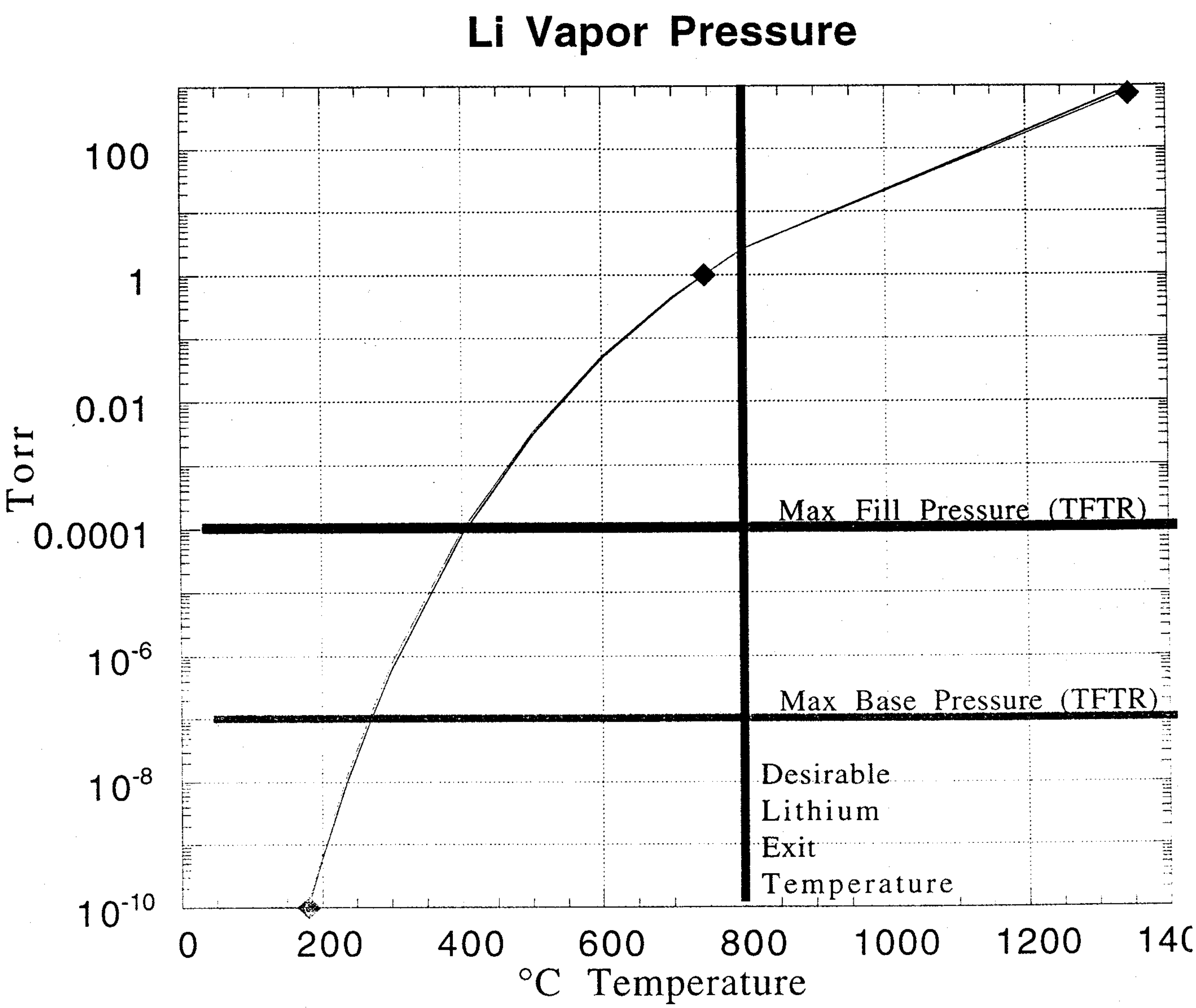
$$| J \times B | > \rho g \cos \theta$$

Confinement is guaranteed if

J (amperes/square meter) > 5047/B (Tesla)

Electrical Separation of Inner and Outer Liquid Walls





Li Vapor Pressure
Torr
100
1
0.01
0.0001
10^{-6}
10^{-8}
10^{-10}
0
200
400
600
800
1000
1200
140
°C Temperature
Max Fill Pressure (TFTR)
Max Base Pressure (TFTR)
Desirable
Lithium
Exit
Temperature

•IT IS NOT KNOWN AT THE PRESENT TIME WHETHER THE VAPOR PRESSURE OF THE PLASMA-FACING LIQUID LITHIUM SURFACE MUST BE RESTRICTED TO EXTREMELY LOW LEVELS IN ORDER TO AVOID COMPROMISING DT PLASMA MAGNETIC CONFINEMENT.

•IF NECESSARY, A LOW VAPOR PRESSURE SURFACE WILL BE ACHIEVED BY SUPPLYING EACH OF THE TWO LIQUID LITHIUM STREAMS INJECTED INTO THE TOP OF THE VESSEL AS TWO ADJACENT LIQUID LITHIUM SUBLAYERS.

•THE TWO SUBLAYERS WILL NOT MIX OR INTERCHANGE BECAUSE LIQUID METAL FLOWS IN A STRONG MAGNETIC FIELD ARE LAMINAR RATHER THAN TURBULENT.

•THE INNER SUBLAYERS (I.E., CLOSEST TO THE PLASMA) WILL BE SUPPLIED WITH RELATIVELY COLD LIQUID. THESE PLASMA-FACING LIQUID LITHIUM SUBLAYERS WILL DESCEND THE CHAMBER RAPIDLY AND EXIT STILL SOMEWHAT COOL AT THE CHAMBER'S BOTTOM, HAVING ABSORBED ONLY THE 16% OF TOTAL (DT+Li) PLANT POWER RESULTING FROM ALPHA PARTICLE HEATING.

•AFTER EXITING, THE STILL SOMEWHAT COOL LIQUID LITHIUM WILL BE PUMPED BACK TO THE TOP OF THE CHAMBER AND REINJECTED TO BECOME THE OUTER SUBLAYER, LOCATED MORE DISTANT FROM THE PLASMA.

•IN THIS POSITION THE LIQUID IS MORE CLOSELY COUPLED BY MECHANICAL AND ELECTROMAGNETIC FRICTION WITH THE CHAMBER'S WALLS. IT THUS DESCENDS MORE SLOWLY. FORMING A THICKER SUBLAYER, WHILE BEING INTERNALLY HEATED BY THE 63% OF PLANT POWER RESULTING FROM 14 MEV NEUTRON FLUX AND THE 21% OF PLANT POWER WHICH ACCOMPANIES TRITIUM PRODUCTION.

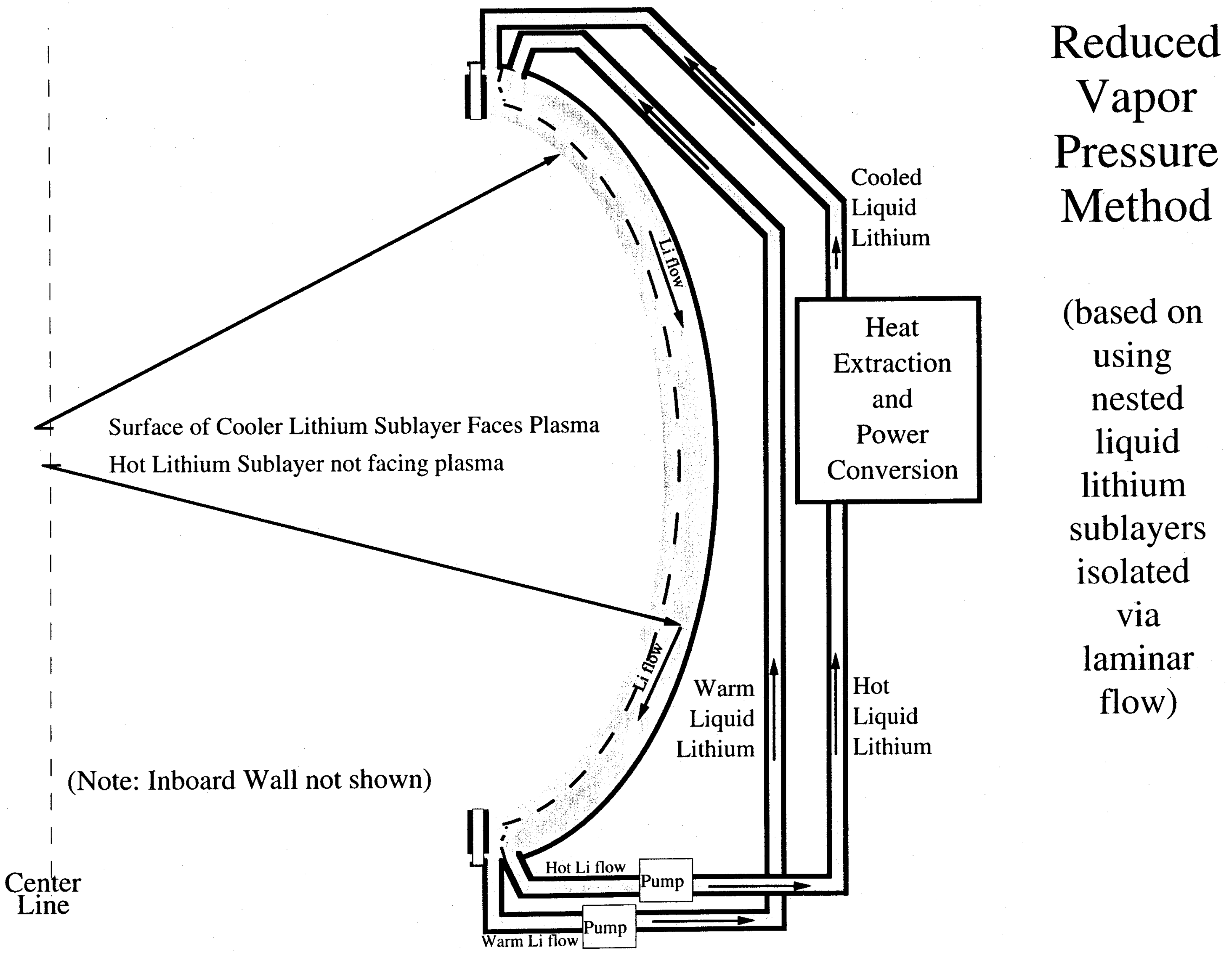
FOR INSTANCE,

•LITHIUM SUPPLIED TO THE INNER SUBLAYER AT A TEMPERATURE SLIGHTLY ABOVE ITS MELTING POINT (E.G., 181°C, WITH A VAPOR PRESSURE OF 10^{-10} TORR) COULD EXIT THE CHAMBER AT 271°C AFTER ABSORBING ALL ALPHA POWER, THUS RESTRICTING THE LIQUID LITHIUM SURFACE'S MAXIMUM VAPOR PRESSURE TO 10^{-7} TORR.

•AFTER REINJECTION AS THE OUTER SUBLAYER, THE SAME LITHIUM WOULD FINALLY REEMERGE AT 745°C, WHICH IS SUFFICIENTLY HOT FOR EFFICIENT ELECTRICAL POWER PRODUCTION.

•LAMINAR FLOW ENSURES THAT THIS HOT EXITING LIQUID LITHIUM (WITH 1 TORR VAPOR PRESSURE) WILL NEVER DIRECTLY FACE THE PLASMA.

NOTE:
MORE THAN TWO SUBLAYERS COULD ALSO BE CONSIDERED.



Reduced Vapor Pressure Method
(based on using nested liquid lithium sublayers isolated via laminar flow)
Cooled Liquid Lithium
Heat Extraction and Power Conversion
Li flow
Surface of Cooler Lithium Sublayer Faces Plasma
Hot Lithium Sublayer not facing plasma
Li flow
Warm Liquid Lithium
Hot Liquid Lithium
(Note: Inboard Wall not shown)
Hot Li flow
Pump
Pump
Warm Li flow
Center Line

to relatively large frictional pressure drops and low velocities. However, two attractive alternatives appear possible for use with fusion. The first possibility is to use the liquid-metal MHD loop as the topping unit in a binary steam cycle,[121] while a second possibility is to employ a two-phase MHD cycle. Petrick and co-workers[122,123] have, in fact, proposed the use of a two-phase cycle with a fusion system; we will briefly review their approach, which is illustrated in Fig. 5.39.

As the gaseous working fluid expands and drives the liquid through the MHD generator, energy is transferred to it from the liquid metal. Thus, the generator behaves like an infinite-stage reheat-turbine. Because of this, and because power can be extracted under controlled velocity conditions so as to minimize friction, the efficiency of a two-phase generator cycle is potentially higher than that for a single-phase generator.

The liquid and gas are mixed at constant pressure and enter the MHD generator where work is extracted at roughly constant velocity and temperature. The generator is contoured to maintain the velocity; to attain sufficient conductivity, the volumetric gas fraction must be maintained above ~70% at the generator exit. This contouring also has the effect of sustaining a large specific heat for the mixture, thus leading to a small temperature change per unit of energy extracted. The two phases are

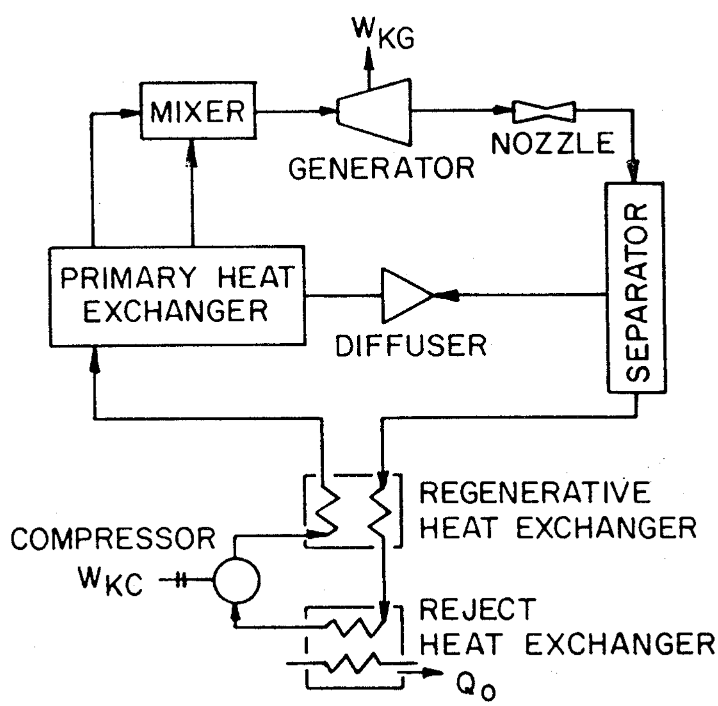


Fig. 5.39. Single-stage two-phase liquid-metal MHD power cycle (from Petrick et al.[122]).

separated on a flat-surface separator after exiting the generator, and the liquid phase is returned to the mixer via a diffuser. The gaseous phase enters the compression loop through a regenerative heat exchanger and a reject (waste heat) heat exchanger. The heat added to the cycle from the fusion reactor can be transferred to either of the fluids (or to both simultaneously).

Calculated overall cycle efficiencies for He-Li mixtures are shown in Fig. 5.40 as a function of the exit void fraction for mixture temperatures from 1000 to 2000°F. (Other calculations show that He-Li mixtures offer somewhat higher efficiencies than do A-Li, He-Na, or Ar-Na mixtures.)

Comparison with Fig. 5.35 indicates that for a fixed maximum cycle temperature, the efficiency of the two-phase MHD cycle falls somewhat below that of the potassium binary cycle. However, the two-phase MHD cycle has a potential advantage in that it eliminates moving machinery such as high-speed turbines. Before a full evaluation is possible, however, a number of potential problem areas must be considered.

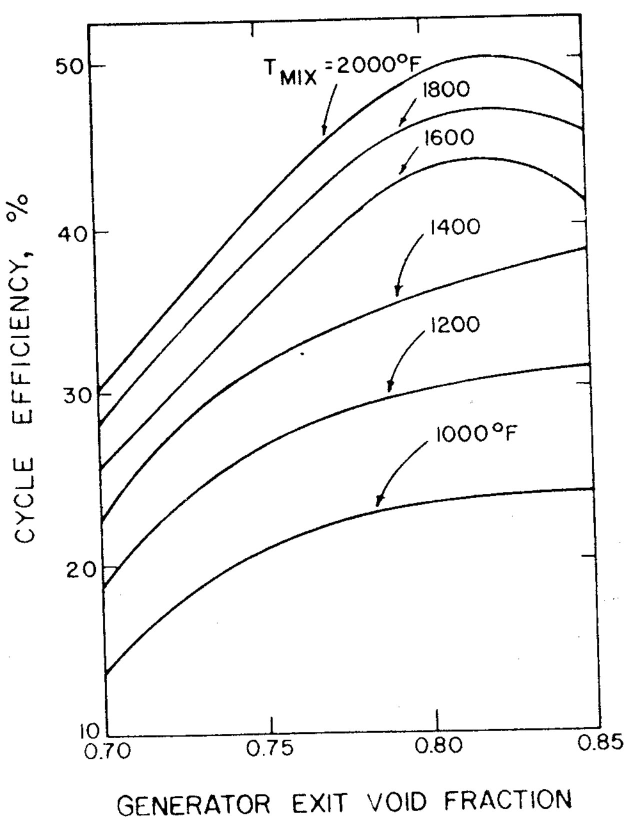
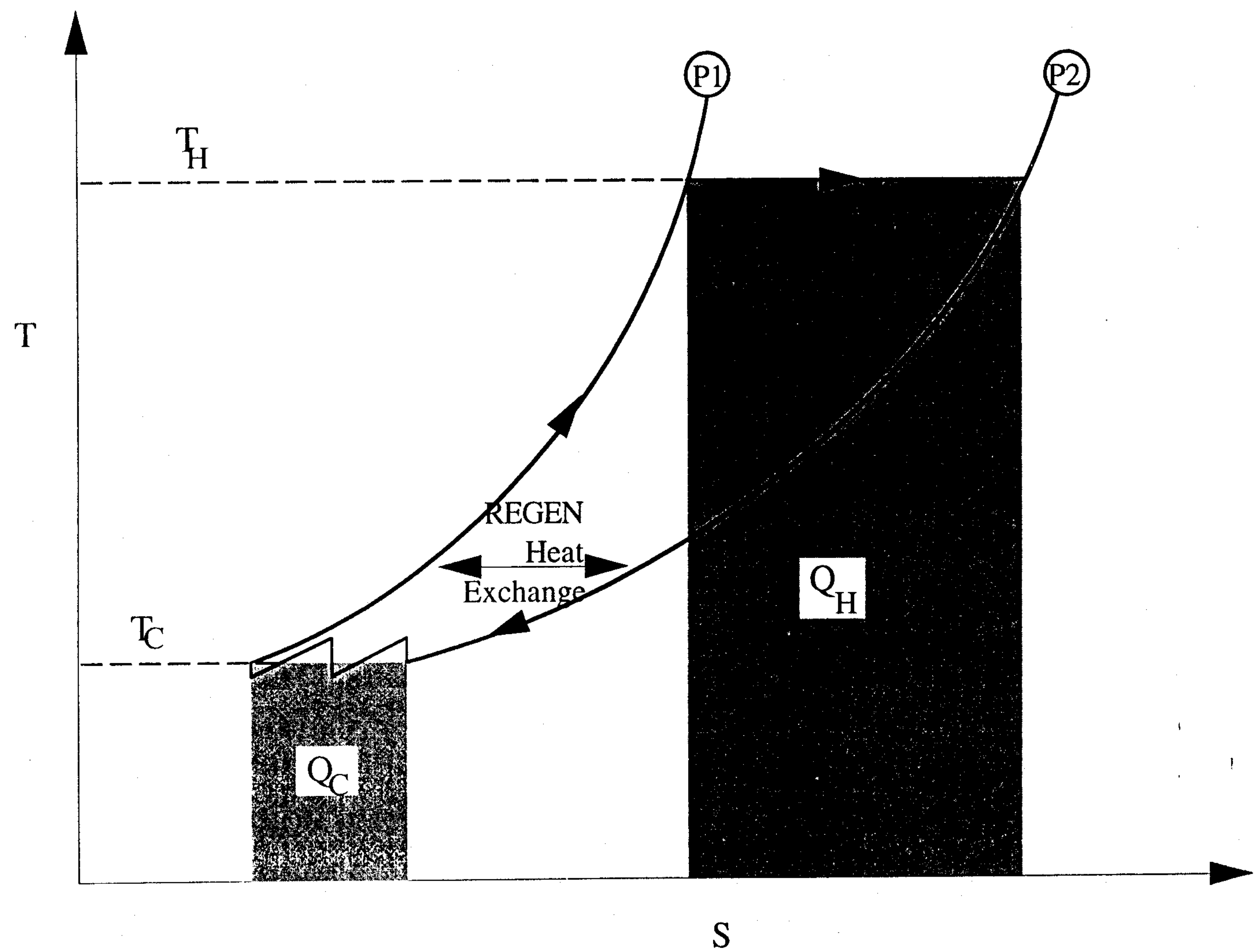


Fig. 5.40. Estimated efficiencies for various mixer temperatures and void fractions, using a two-phase liquid-metal MHD (from Petrick et al.[122]), assuming a He-Li mixture at 750 psia, and neglecting volatility effects.

ERICSSON PROCESS USED IN LMMHD POWER GENERATION .



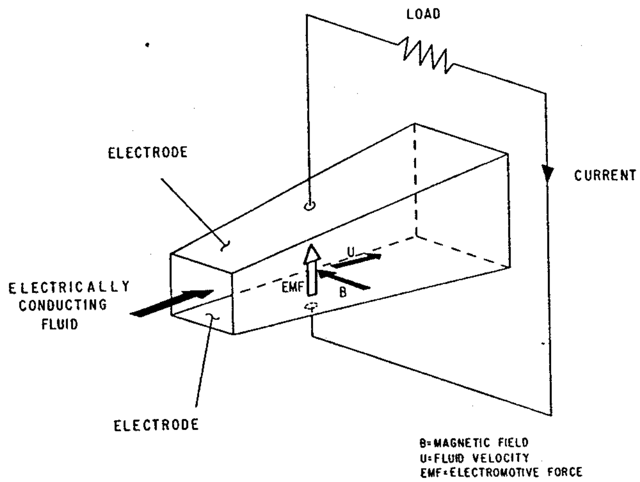


Fig. 1 Principle of the MHD Generator

LIQUID-METAL MAGNETOHYDRODYNAMICS

Cycles

The two-phase-generator liquid-metal MHD (LMMHD) cycles use two working fluids, a thermodynamic fluid (gas or vapor) and an electrodynamic fluid (liquid metal) to provide the electrical conductivity in the LMMHD generator. The two working fluids give LMMHD great versatility in coupling to different heat sources and operating over different temperature ranges. The cycle configurations currently under investigation are: 1) the Rankine-cycle version best suited to heat-source temperatures of 370 K to ~850 K (Ref. 5), 2) the Brayton-cycle version best suited to heat-source temperatures above ~730 K (Ref. 6), and 3) the open-cycle version for coal or other fossil fuels (Ref. 7).

The Brayton-cycle (gas-cycle) LMMHD concept schematic diagram with a gas turbine is shown in Fig. 2. An inert gas, e.g., helium, is the thermodynamic working fluid, and a liquid metal, e.g., sodium or lithium, is the electrodynamic fluid in the MHD generator. In operation, the gas and liquid are combined in the mixer and the resulting two-phase mixture enters the MHD generator. The MHD generator acts as a combined turbine and electric generator; the gas expands, drives the liquid across the magnetic field, and, thus, generates electrical power. Because the liquid has a high heat (energy) content, expansion occurs at almost constant temperature, and a great deal of energy is still available in the gas that leaves the MHD generator. (The liquid acts as an "infinite-reheat" source for the gas, heat energy is continuously transferred from the liquid to the gas, and most of the energy out of the generator comes from the liquid.) It is this almost-constant-temperature expansion that accounts for the potentially higher efficiency of the two-phase LMMHD concepts. From the MHD generator, the two-phase mixture enters a nozzle, where additional gas-liquid energy is used (as in the generator) to accelerate the liquid; the resulting high-speed flow is separated in a separator (possibly rotating to minimize losses), and the liquid pressure needed to return the liquid through the primary heat exchanger to the mixer is obtained in the diffuser. The nozzle-diffuser system may be replaced by a liquid-metal pump if better performance results.

The gas leaving the separator still has considerable thermal energy, which must be used effectively in order to obtain the highest efficiency for the system. It can be transferred from the hot gas to the colder gas in a regenerator, extracted with a gas turbine, extracted with a steam boiler (which would replace both the gas turbine and regenerator of Fig. 2), or used to provide heat for some other process in what is termed "cogeneration." These components can be combined.

Heat addition can be to the liquid metal, the gas, or both. Because the liquid-metal mass flow rate is much higher than the gas mass flow rate the heat addition can be solely to the liquid metal, with the gas being heated by the liquid in the mixer, to yield a simpler system without a significant effect on plant efficiency.

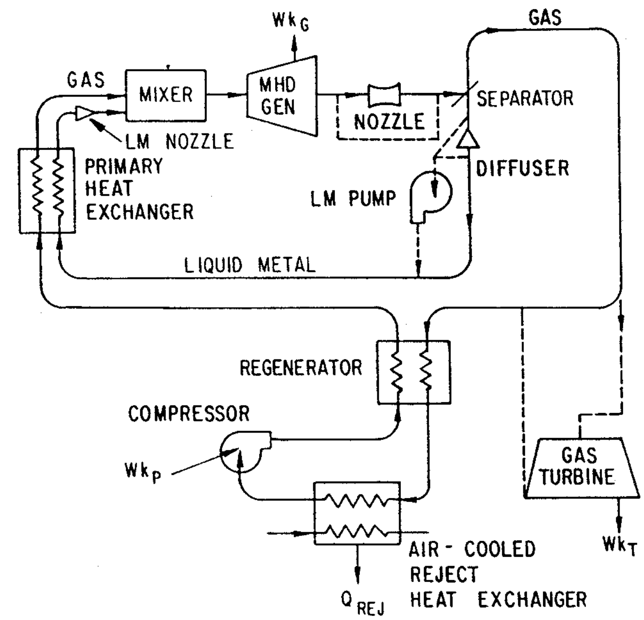


Fig. 2 The Brayton-cycle LMMHD Concept

The Rankine-cycle (vapor-cycle) LMMHD concept differs from the Brayton-cycle version only in the use of a condensable fluid, e.g., steam or neohexane, as the thermodynamic working fluid with a compatible liquid metal, e.g., tin or NaK. Again, the energy in the (superheated) vapor leaving the separator is recovered in a regenerator, a low-pressure turbine, or used for process heat, and heat addition can be solely to the liquid metal, with the vapor being generated from the condensate in a direct-contact mixing boiler. Because of the almost-constant-temperature expansion, LMMHD Rankine-cycle calculated efficiencies are higher than those of conventional plants for the same source and sink temperatures. The LMMHD Rankine cycle is also under consideration for high-temperature space power systems with, for example, cesium as the vapor and lithium as the liquid metal (Ref. 8). Temperatures would be above 900 K.

The open-cycle version differs from the Brayton-cycle version in using an open rather than a closed gas cycle. Combustion gas (from coal or other fossil fuels) is used as the thermodynamic fluid with a compatible liquid metal, most likely copper or a copper alloy, thereby eliminating the need for a primary heat exchanger. Coal is burned with air in a pressurized, vortex-type combustor (similar to a conventional cyclone furnace). The combustion products go from the combustor to the LMMHD mixer, where they are mixed with the liquid metal; thus, the liquid is heated by the combustion gas in the mixer. The two-phase and pure-liquid-metal components are the same as for the other versions. Leaving the LMMHD loop, the energy remaining in the combustion gas is used in a conventional boiler plant, a gas turbine, or a process heat application.

Components

The two-phase LMMHD generator is the key component in the cycle, and the most unusual. It inherently has a high efficiency if the loss mechanisms not basic to its operation replace by viscous losses and slip losses can be controlled. Thus, research has focused on studiesof the individual losses, studies of two-phase flows in a magnetic field, and generator models and experiments as described below:

(1) End losses i.e., ohmic losses due to current reversal in the generator end regions as a result of spatially decreasing magnetic fields, set a lower limit to the generator's length and an upper limit to the generator's voltage. Early work established the use of insulating vanes (Ref. 9) and multiple generators (Ref. 10) to minimize end currents and losses. A numerical model allows the calculation of the end loss for an arbitrary arrangement of insulating vanes (number, lengths, locations) (Ref. 11).

(2) Viscous losses (due to wall shear) are small because the electromagnetic forces are so much larger than all other forces. However, wall shear causes a pure-liquid shunt layer adjacent to the wall with a low velocity. Current reversal occurs in this layer, and the effect of the current reversal is magnified because the liquid conductivity is higher than the two-phase core flow conductivity. Analysis has shown this effect to be very small (Ref. 12).

(3) Slip, where the gas velocity is higher than the liquid velocity, reduces the efficiency of the generator and the cycle. The most-recent data clearly shows that at higher electromagnetic interactions the slip loss is small (Ref. 13).

To better understand LMMHD generators, basic studies have been made. These have included experiments focused on single- and two-phase flows in the generator (Ref. 14), the electrical conductivity of two-phase mixtures (Ref. 15), and the slip under different conditions (Ref. 16).

The impact of the above work on generator efficiency is dramatically demonstrated by the data of Fig. 3 (Ref. 13). The efficiency has increased with experience, and for the most recent channel (LT-4) is substantially higher at high void fractions. The power density is comparable to or above that anticipated for commercial generators, thus minimizing the chances of encountering unanticipated problems in scaling to larger generators. Efficiencies in excess of 0.60 were obtained with a small generator [~20 kW(e)] which had no provision (such as vanes) to minimize end losses.

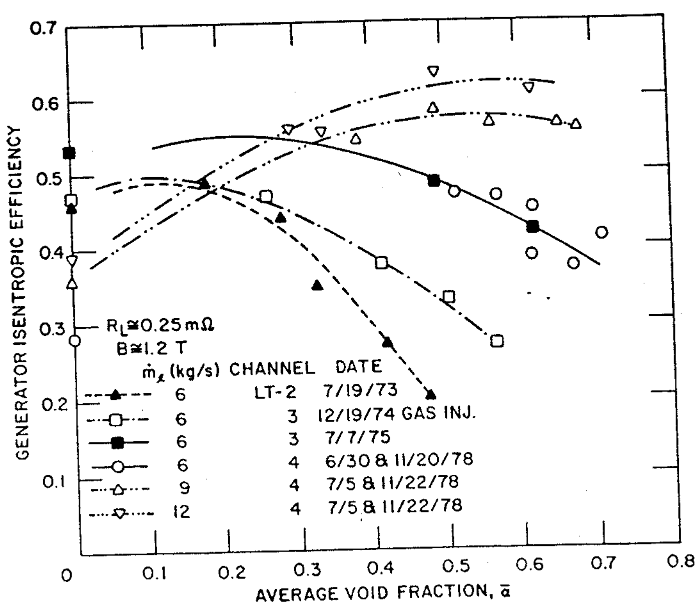


Fig. 3 LMMHD Generator Efficiency versus Void Fraction

There is a substantial body of two-phase literature, much of which is applicable to mixers, nozzles, diffusers, and separators for LMMHD systems. Experiments have established mixer characteristics under various operating conditions (Refs. 17,18), and the results indicate that element and contraction-geometry designs are the most critical factors. Both two-component, two-phase and one-component, two-phase nozzles have been studied, as well as two-phase diffusers (Ref. 19).

High-performance gas-liquid separators have been investigated for many applications. For flat-plate separators, excellent agreement was obtained between the test results and model (Ref. 19). A novel impinging-jet separator showed significant liquid concentration (>3 to 1) is possible with very low velocity losses (Ref. 19). Rotating separators, which minimize the viscous loss, are very attractive. Biphase Energy Systems has considerable experimental experience, including field tests, with rotary separator turbines for generating power from geothermal brines (Ref. 20).

BACKGROUND for (2): In the past there has been study of schemes to generate "liquid metal magnetohydrodynamic" (LMMHD) electric power using, for the thermodynamic working fluid, a two-phase combination of hot liquid lithium and helium bubbles (injected and re-extracted within the power conversion loop).

IDEA (2): Locate a <u>LMMHD electrical power generation system within the blanket region</u> of a fusion reactor and directly integrate it with the blanket, in order to use the plasma's confining TF magnet as the LMMHD power production magnet, and in order to reduce heat exchanger requirements.

BENEFITS of (2)

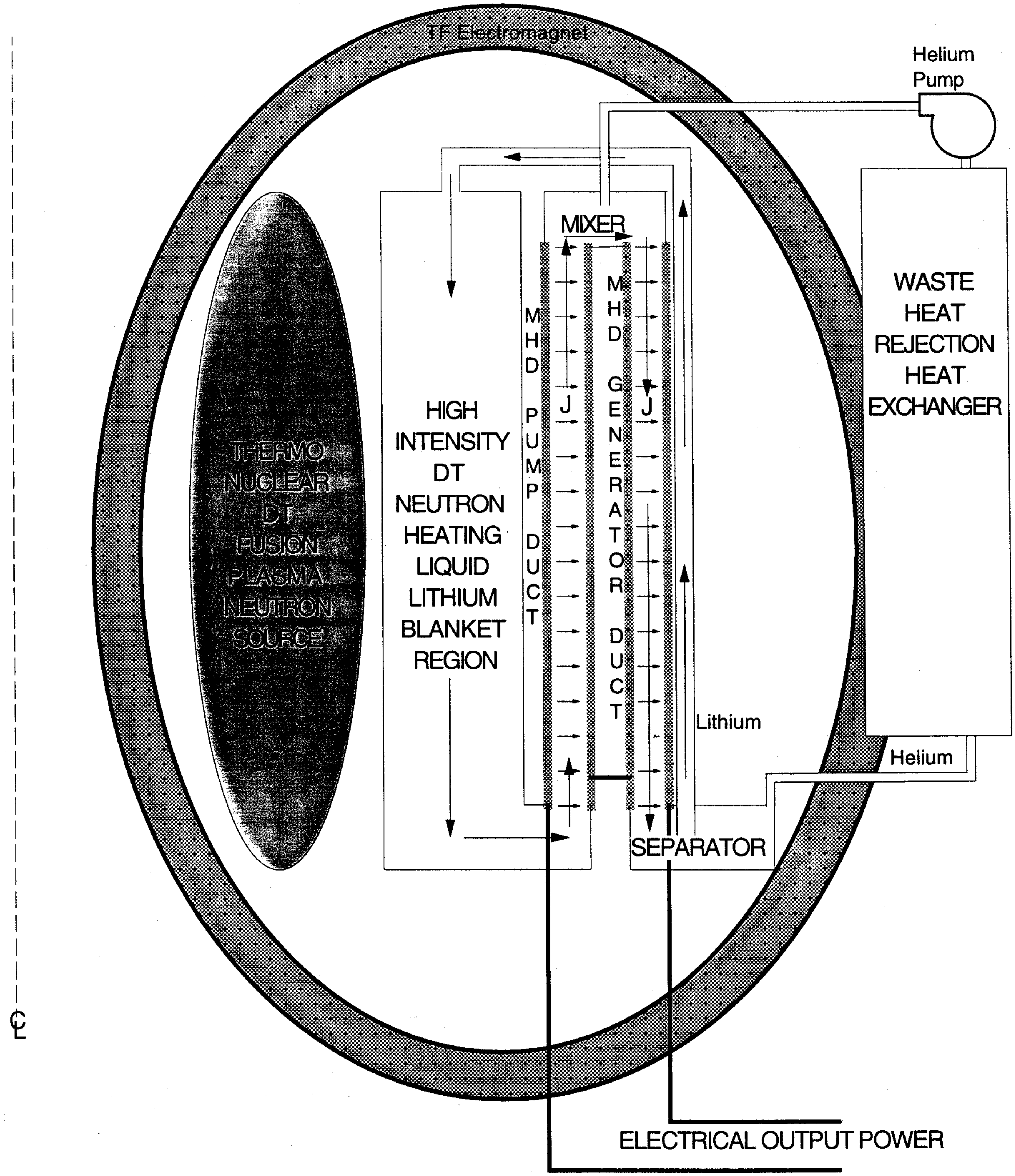
(1) THE TOTAL CAPITAL COST OF FUSION POWER WILL BE REDUCED BECAUSE THE "BALANCE -OF-PLANT" EQUIPMENT IS SIMPLIFIED. (THERE IS NO POWER-PRODUCING TURBINE OR ROTATING ELECTRICAL GENERATOR, AND HEAT EXCHANGERS ARE SIMPLIFIED.)

(2)NO DEDICATED HEAT EXCHANGER IS NEEDED TO TRANSFER FUSION ENERGY TO THE ENERGY CONVERSION FLUID, SINCE IT IS DIRECTLY HEATED BY FUSION NEUTRONS.

(3)INSTEAD OF SPECIALIZED LMMHD ELECTROMAGNETS, THIS USES THE AMBIENT TOROIDAL MAGNETIC FIELD WHICH NECESSARILY EXISTS FOR MAGNETIC PLASMA CONFINEMENT REASONS WITHIN THE FUSION BLANKET REGION.

(4)SAFETY AND RELIABILITY ARE IMPROVED BECAUSE THERE ARE FEWER TYPES OF POSSIBLY INTERACTING MATERIALS IN A FUSION REACTOR USING THIS IDEA. THE FUSION BLANKET TRITIUM BREEDING MATERIAL, LIQUID LITHIUM, IS IDENTICALLY THE SAME MATERIAL WHICH IS USED FOR THE THERMODYNAMIC ENERGY CONVERSION WORKING FLUID. EVEN THE HELIUM COMPONENT OF THE ENERGY CONVERSION FLUID MATCHES THE HELIUM NATURALLY PRODUCED IN LITHIUM AS A BYPRODUCT OF TRITIUM BREEDING.

(5) THE INTRINSIC HELIUM INSERTION AND EXTRACTION FEATURES OF THE LMMHD SCHEME CONTINUOUSLY "SPARGE" THE LIQUID LITHIUM, WHICH MAY HELP IN THE CONTINUOUS REMOVAL OF BRED TRITIUM FROM THE BLANKET.



SCHEMATIC DIAGRAM: Direct Production of Electrical Power From Within the Lithium Blanket Region of a Magnetically Confined Deuterium-Tritium Fueled, Thermonuclear Fusion Reactor.

COMBINING IDEAS (1) and (2)

- LMMHD GENERATOR GEOMETRY SHOULD BE AXISYMMETRIC
  TO AVOID PERTURBING PLASMA

- AT LEAST SOME OF THE LITHIUM MUST BE COOLED
  TO LIMIT VAPOR PRESSURE SEEN BY PLASMA
  - -STAGING HAS BEEN INVESTIGATED IN LITERATURE,
    AND COULD BE EFFICIENT
  - (THIS MODIFIES THE ERICSSON PROCESS)

- ELECTRICAL OUTPUT POWER IS
  LOW-VOLTAGE HIGH-CURRENT DC (<45 VOLTS)
  - -CUSTOMER COULD BE HYDROGEN PRODUCTION
  - -POWERING RESISTIVE MAGNETS MAY BE EASIER