Liquid protection reduces COE in three ways:

-3%
liquid protection reduces capital cost, e.g.,fewer hot cells and remote handling equip.

-12%
liquid protection reduces blanket replacement costs

capital charge rate

$$\mathrm{COE} = \frac{C \cdot i + \text{annual blanket replacement cost} + \text{O\&M} \underbrace{\begin{array}{l} + \text{waste disposal} \\ + \text{decommissioning} \\ + \text{fuel cost} \end{array}}_{\text{small}}}{8760 \cdot C_f \cdot P_{fusion} \cdot M \cdot \eta_{th} \cdot (1 - f_{recirculating\ power})}, \text{¢/kWh}$$

-12%
liquid protection increases capacity factor, C_f
by reducing scheduled and unscheduled down time to replace damaged blankets

high gain targets and high driver efficiency reduces f_{recir}, $\eta_d G \sim 18$

$$f_{recir} = \frac{1}{M\eta_{th}\eta_d G} + \frac{P_{pumping} + P_{aux}}{P_{fusion} M \eta_{th}}$$

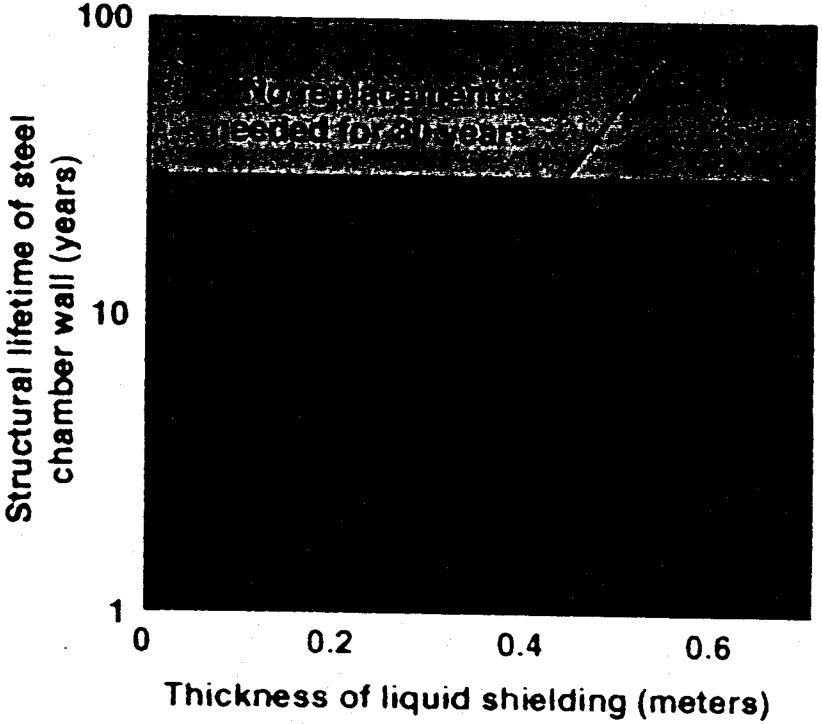
$\eta_i Q$

3/4/96 Moir

IFE power plants can use renewable liquid-protected walls for long life, low radio activity, and low maintenance

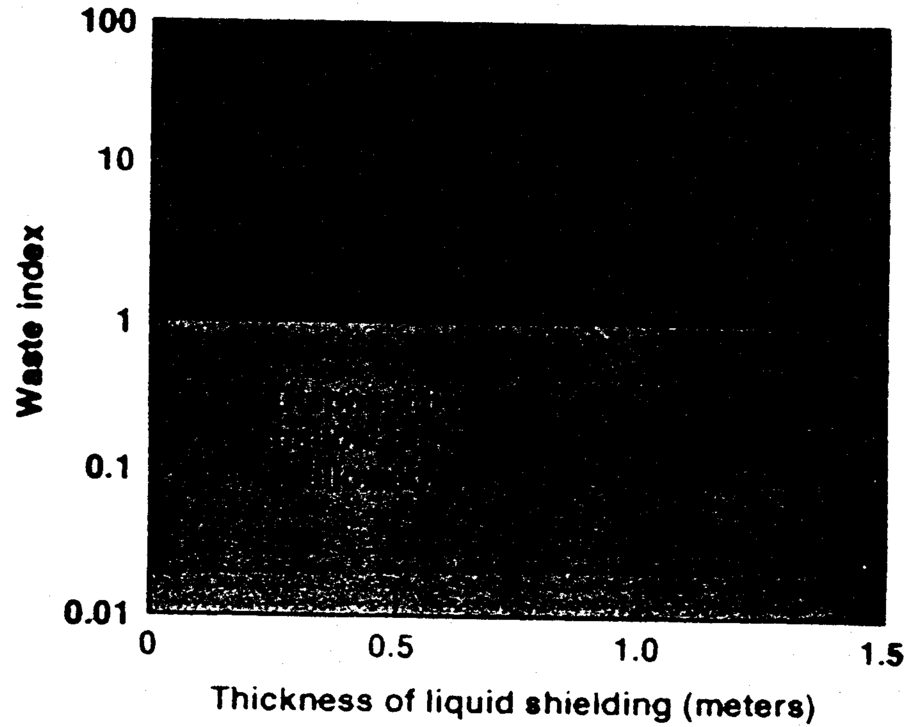
IFE program goals are:

- Avoid replacing damaged materials



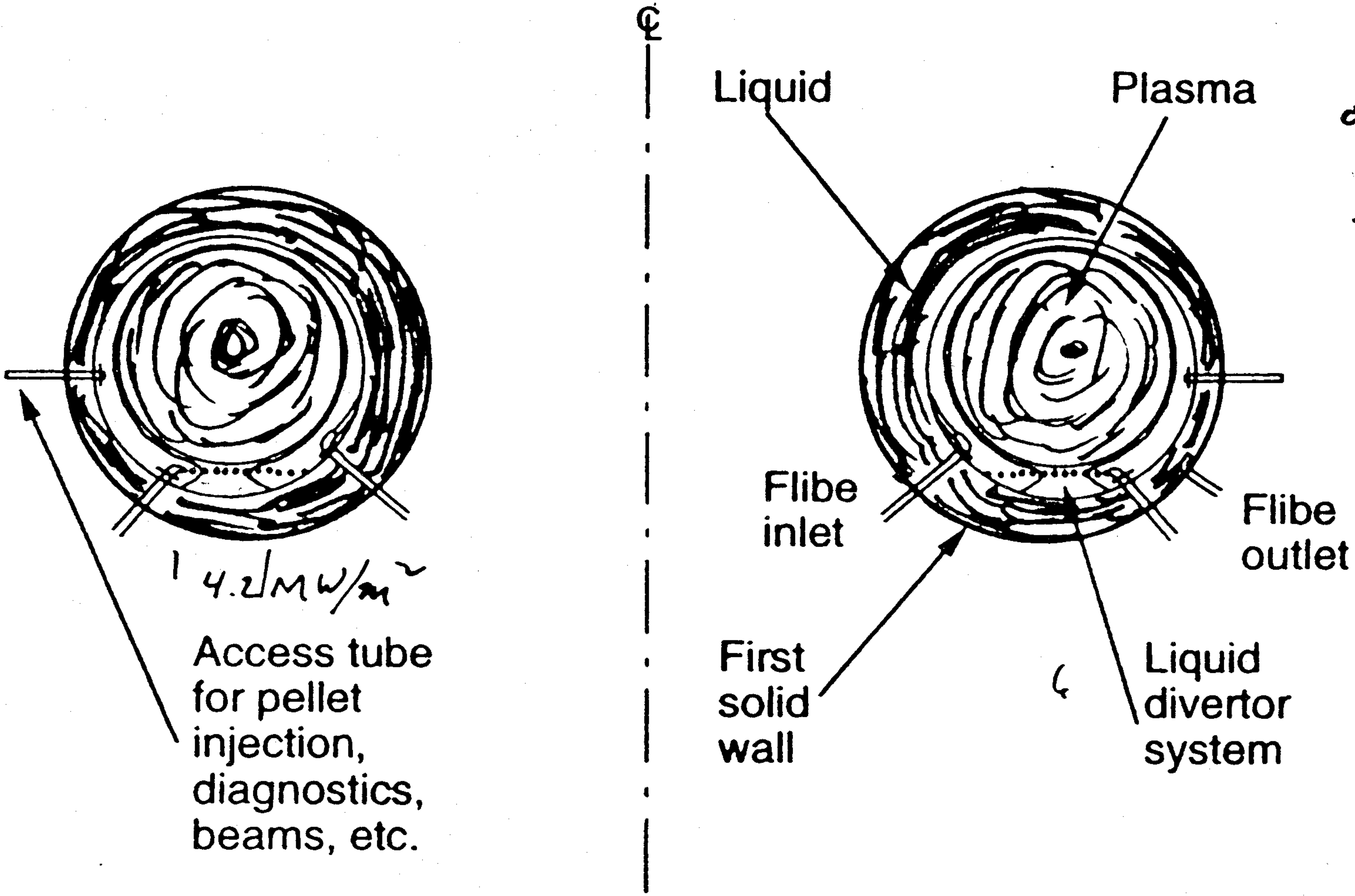
Sumer Sahin, R. W. Moir, A. Sahinaslan, and H. M. Sahin "Radiation damage in liquid-protected first-wall materials for IFE-reactors," *Fusion Technology* 30, 1027–1035 (1996)

- Avoid deep burial of waste



J. D. Lee, "Waste Disposal Assessment of HYLIFE-II Structure," *Fusion Technology* 26, 74 (1994)

- Avoid concrete domes and public evaluation plans
- Avoid generating greenhouse gases



1GWe

6 MW/m^2

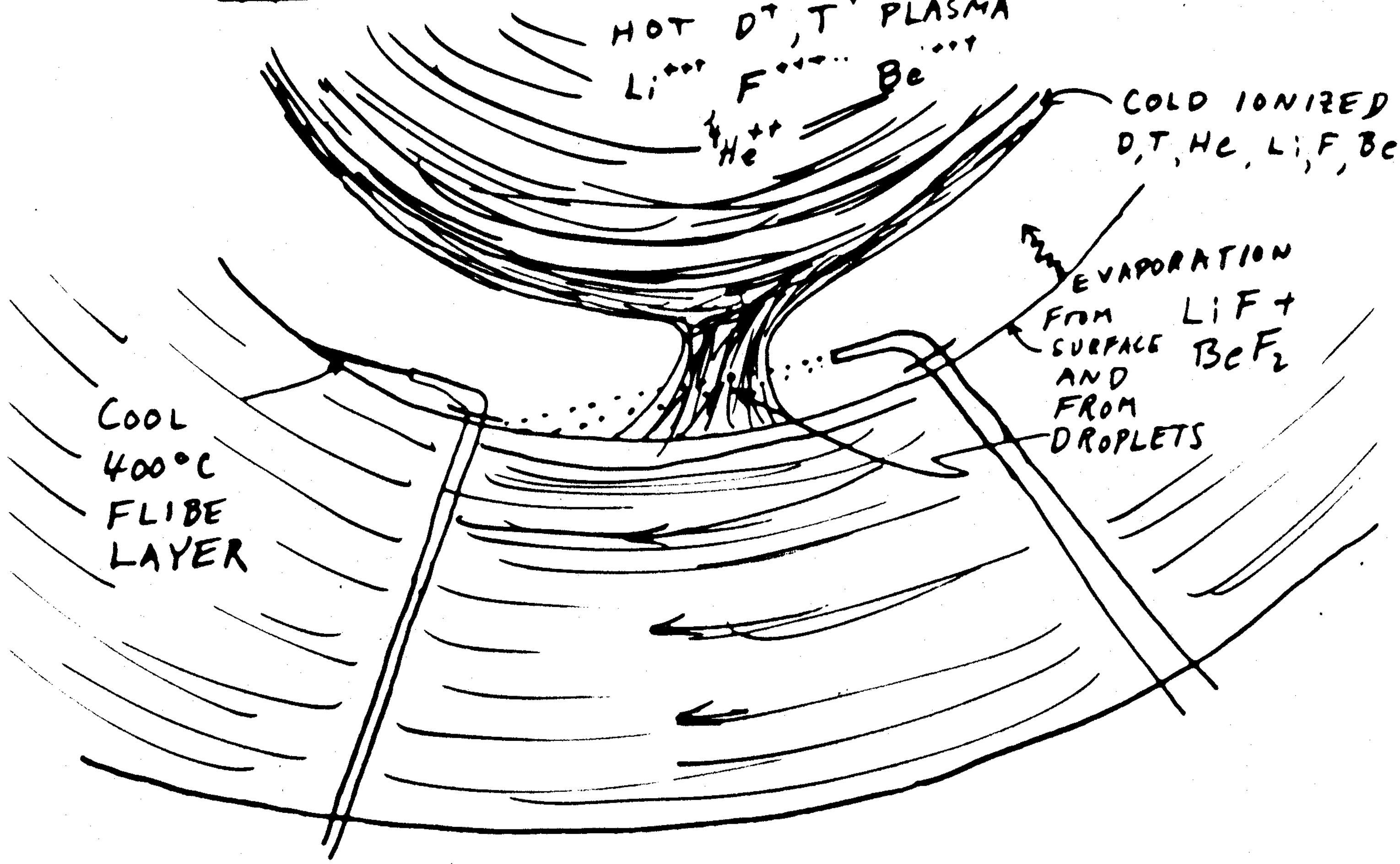
0.1 MW/m^2 surface

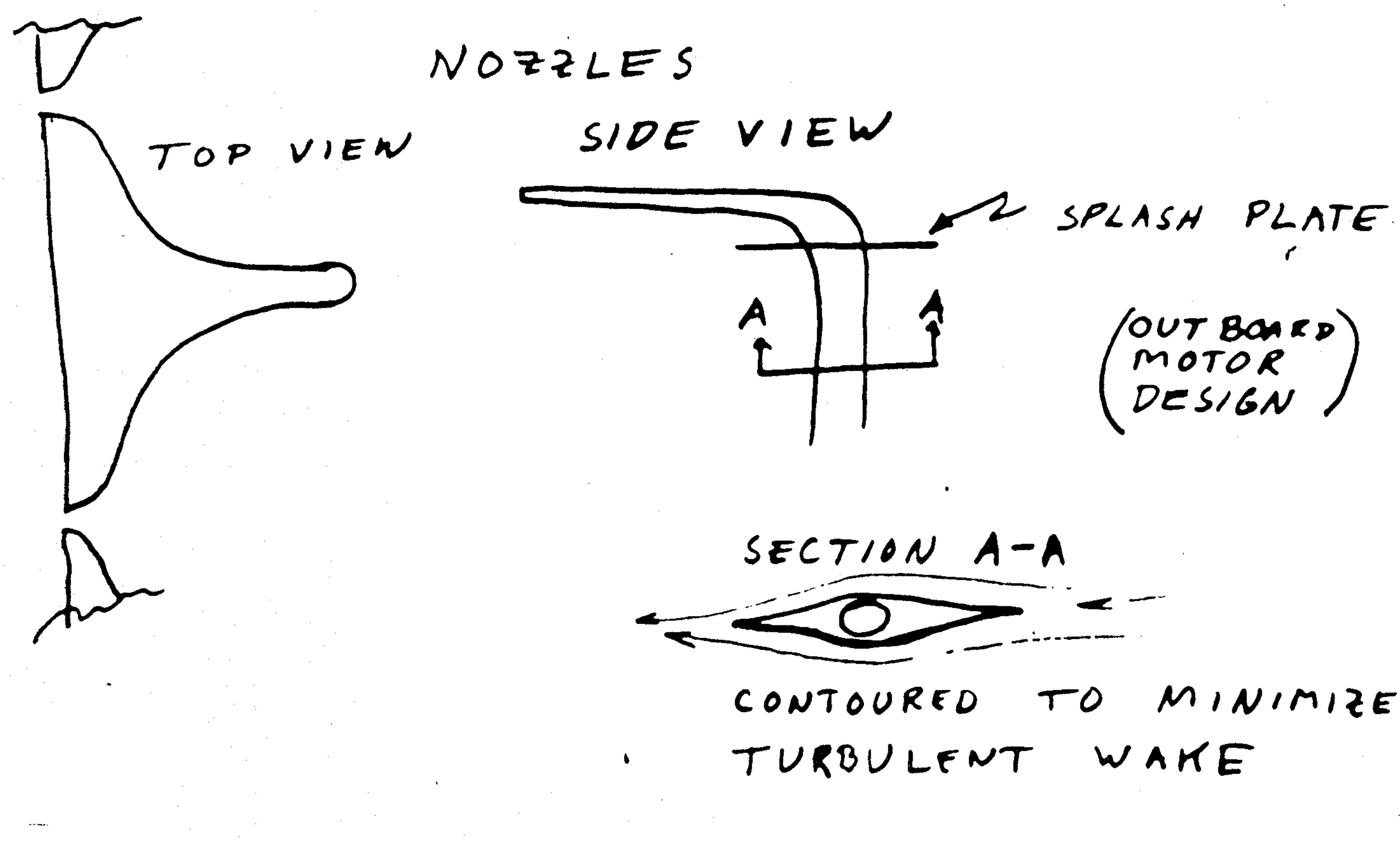
$\Delta T = 20°C$

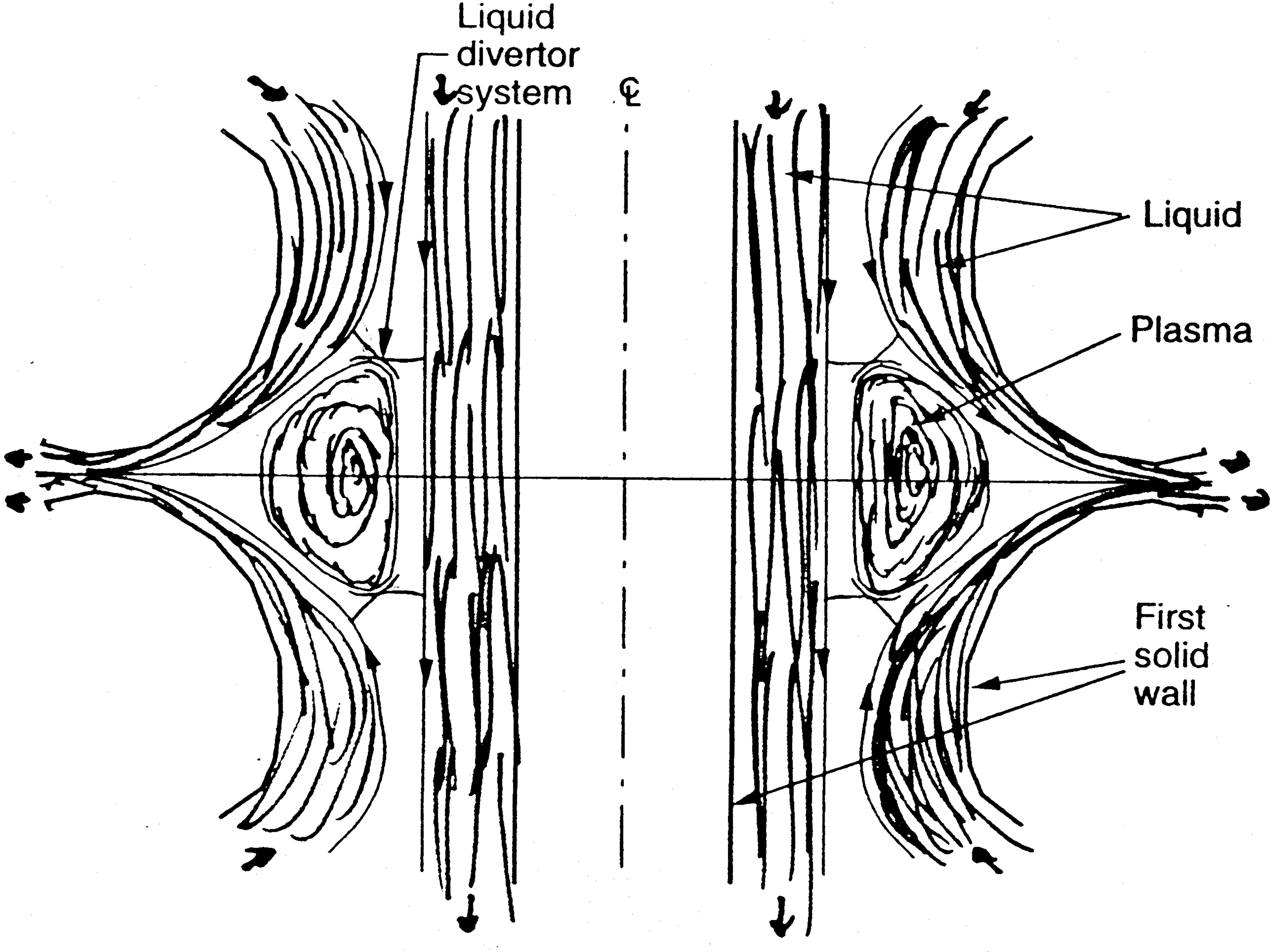
2 rps

Liquid wall Tokamak

ROTATING LIQUID BLANKET

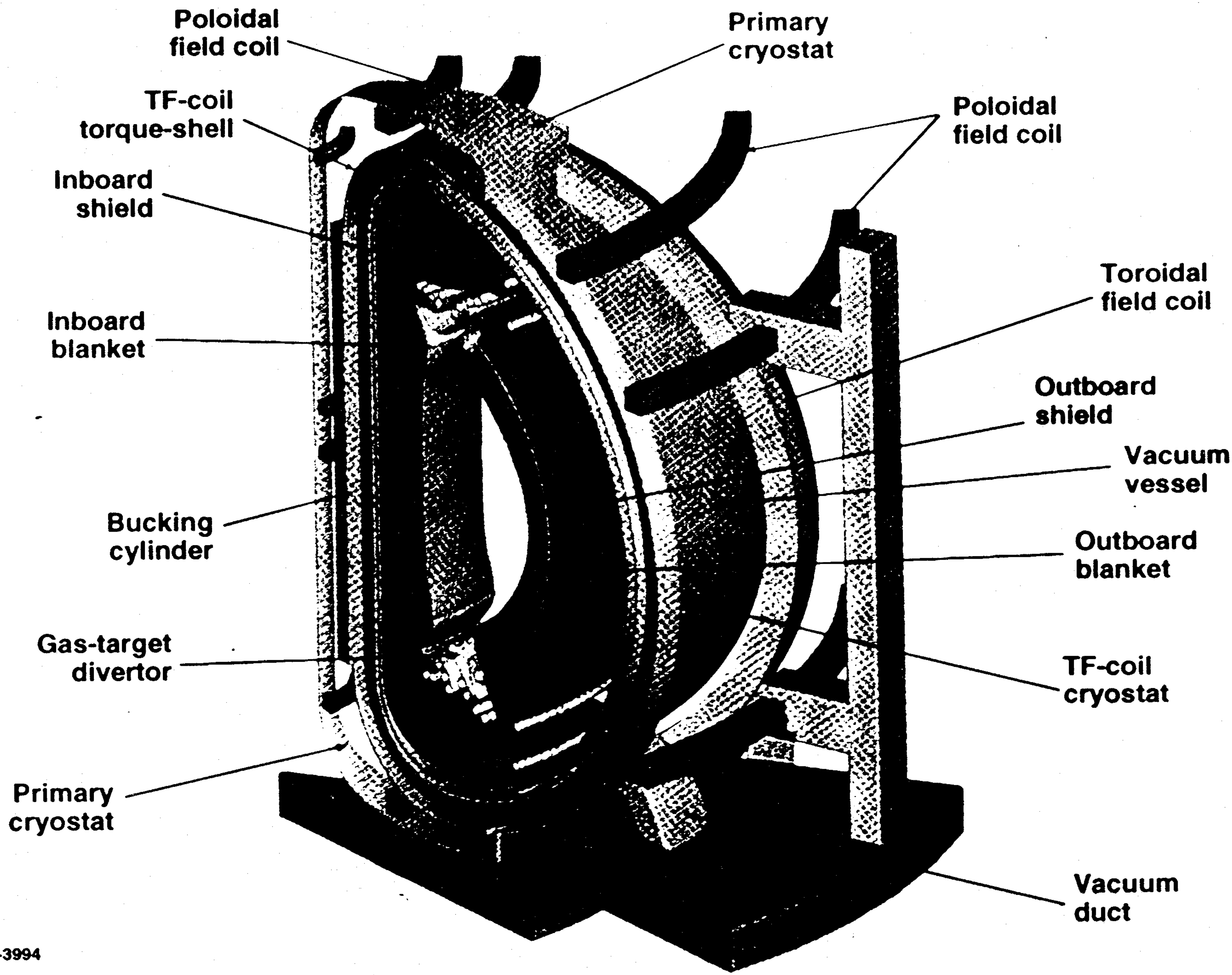




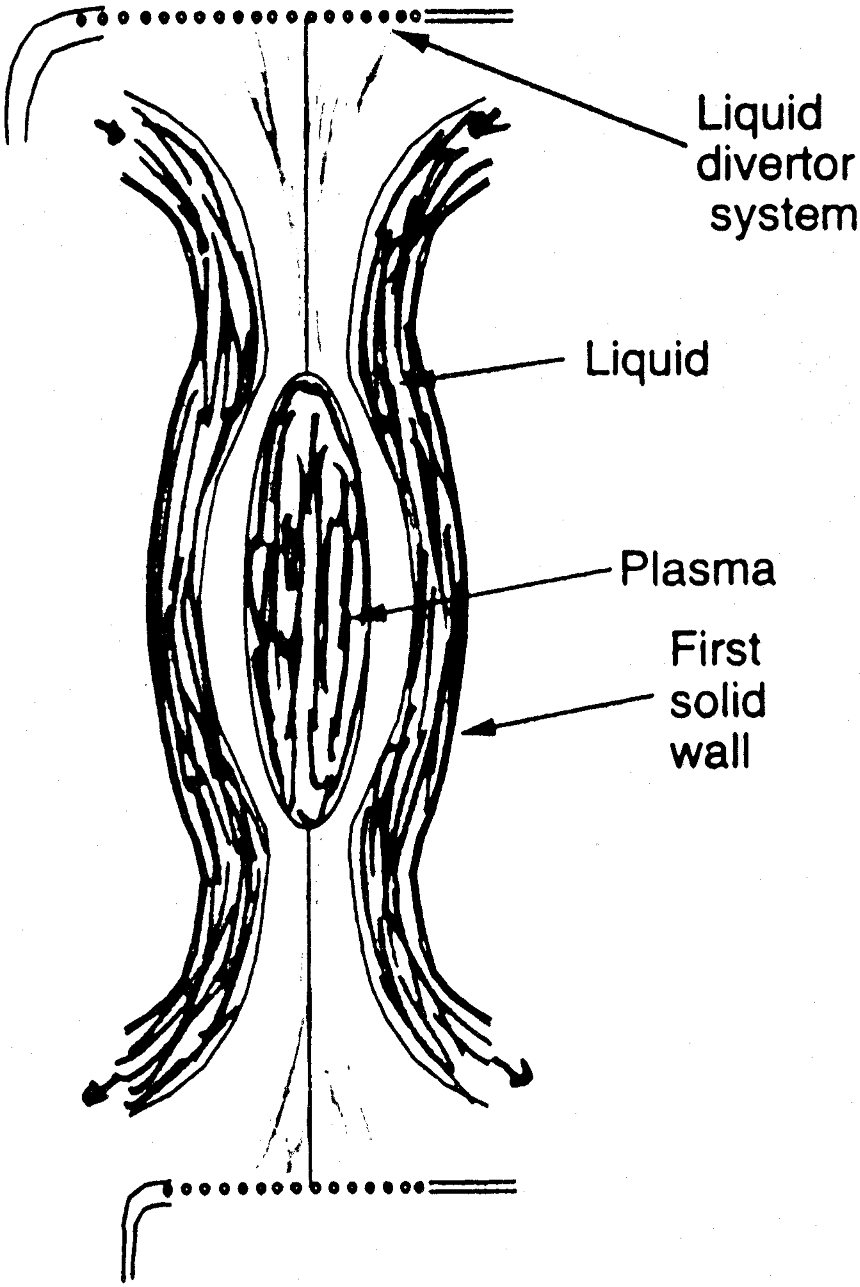


Liquid wall Tokamak

Section of the ARIES-IV Fusion Power Plant



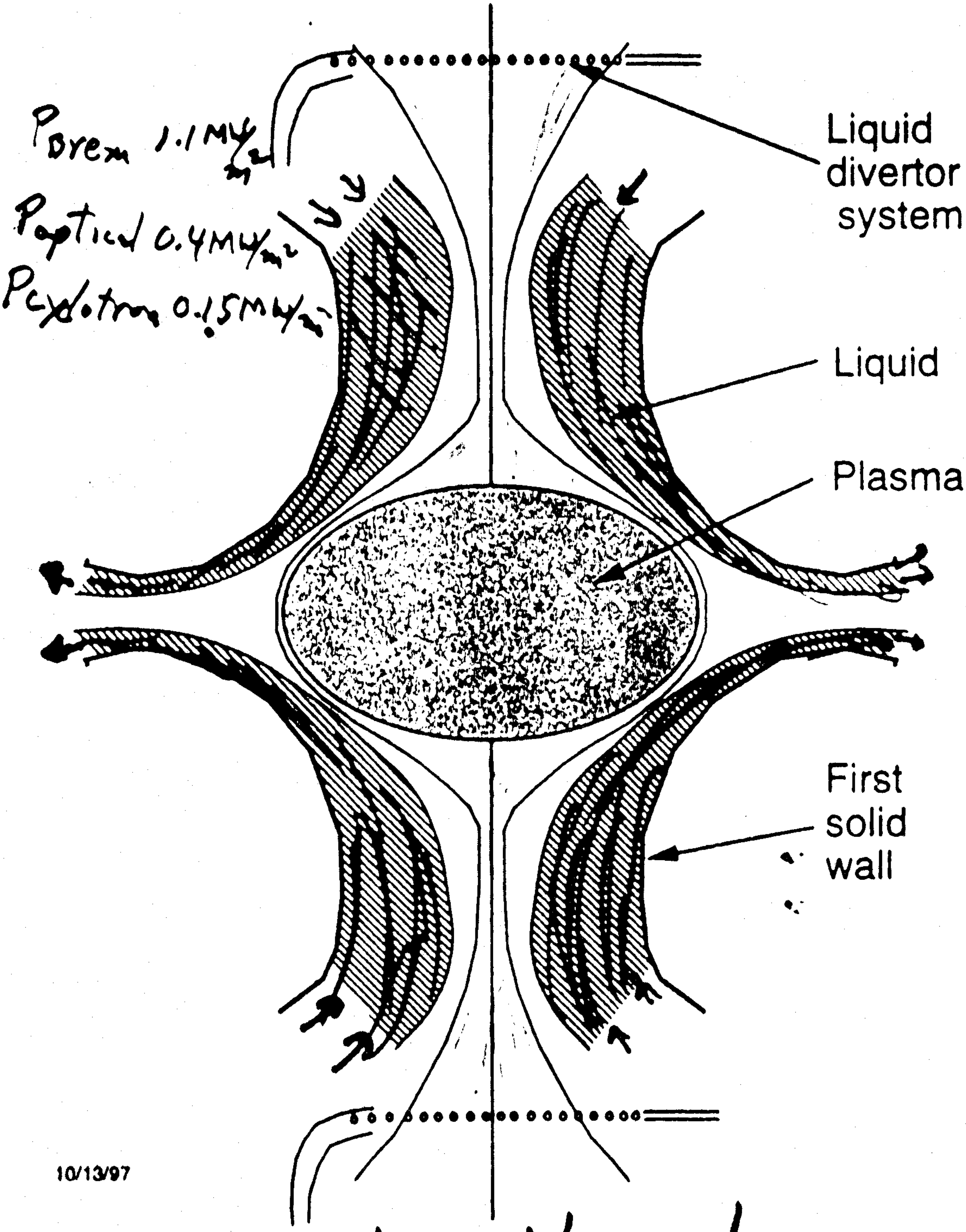
-00-1294-3994
WM/syd



Liquid wall FRC

10 m/S
0.3 s $\Delta T = 160°C$

2GWe
$30 MW_n/m^2$



Liquid wall spheromak

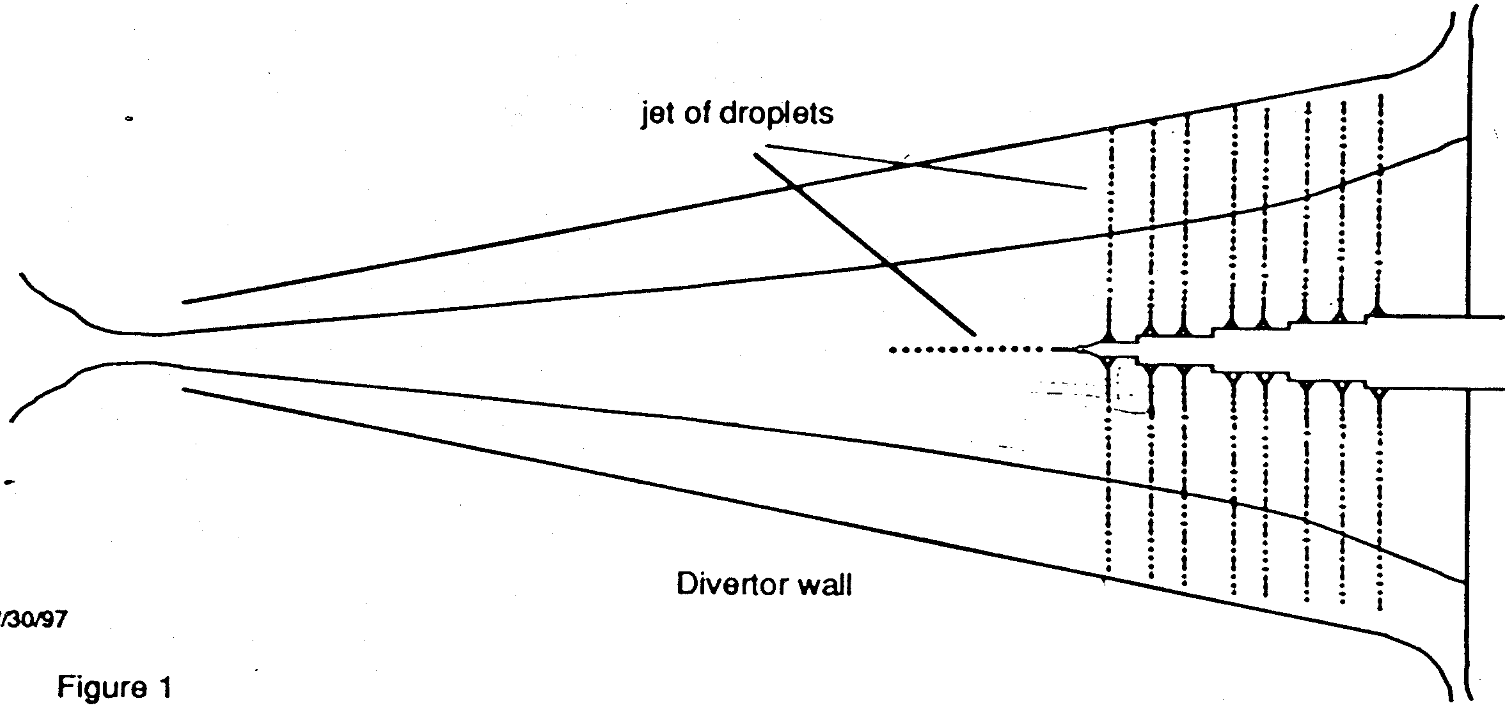


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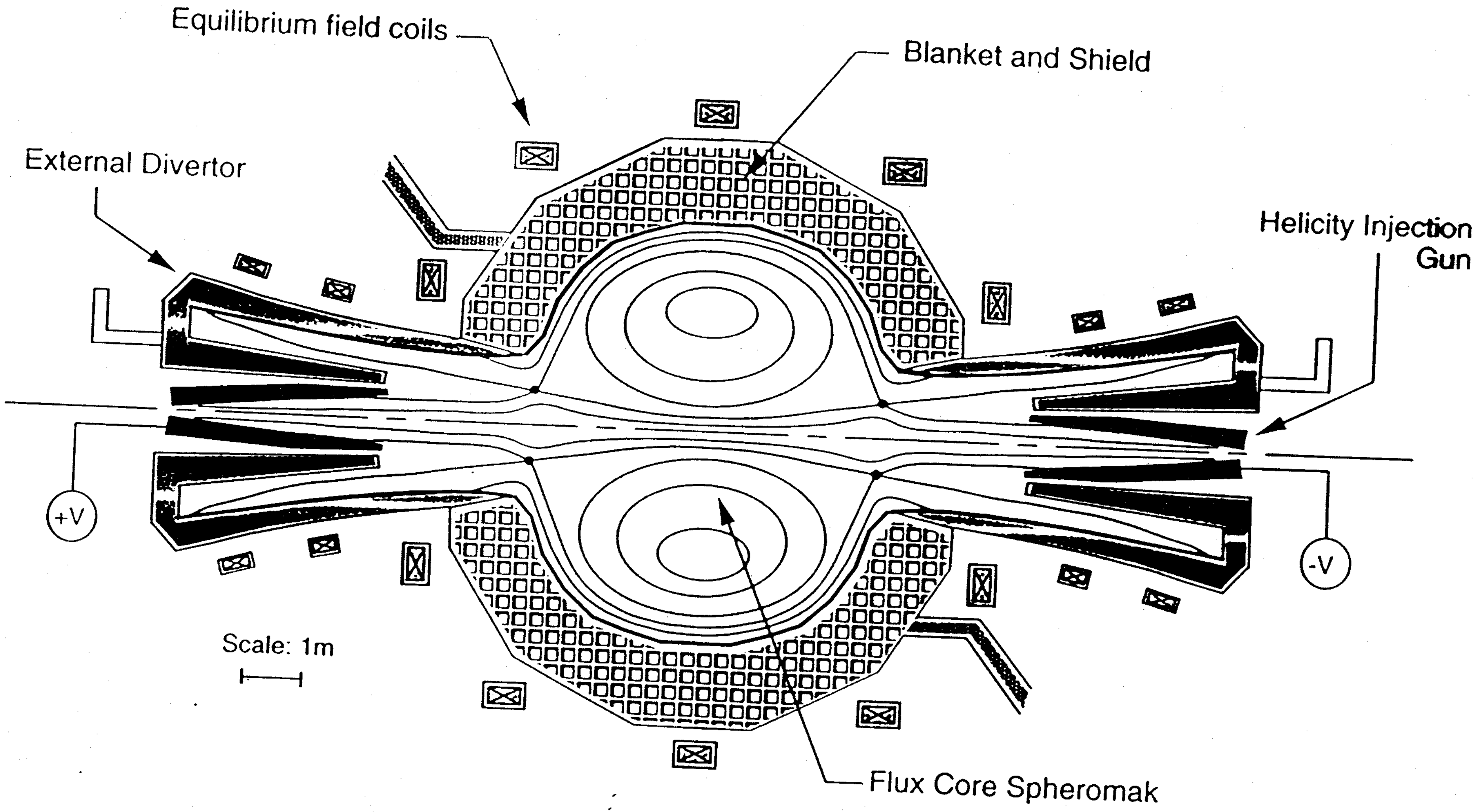
Figure 1
Ultra-high heat flux divertor for alternative magnetic fusion concepts, FRC and Sppheromak



Schematic 1000MWe Flux Core Spheromak Reactor.
(Approximately to scale for a limiting neutron wall load of $10 MW/m^2$)

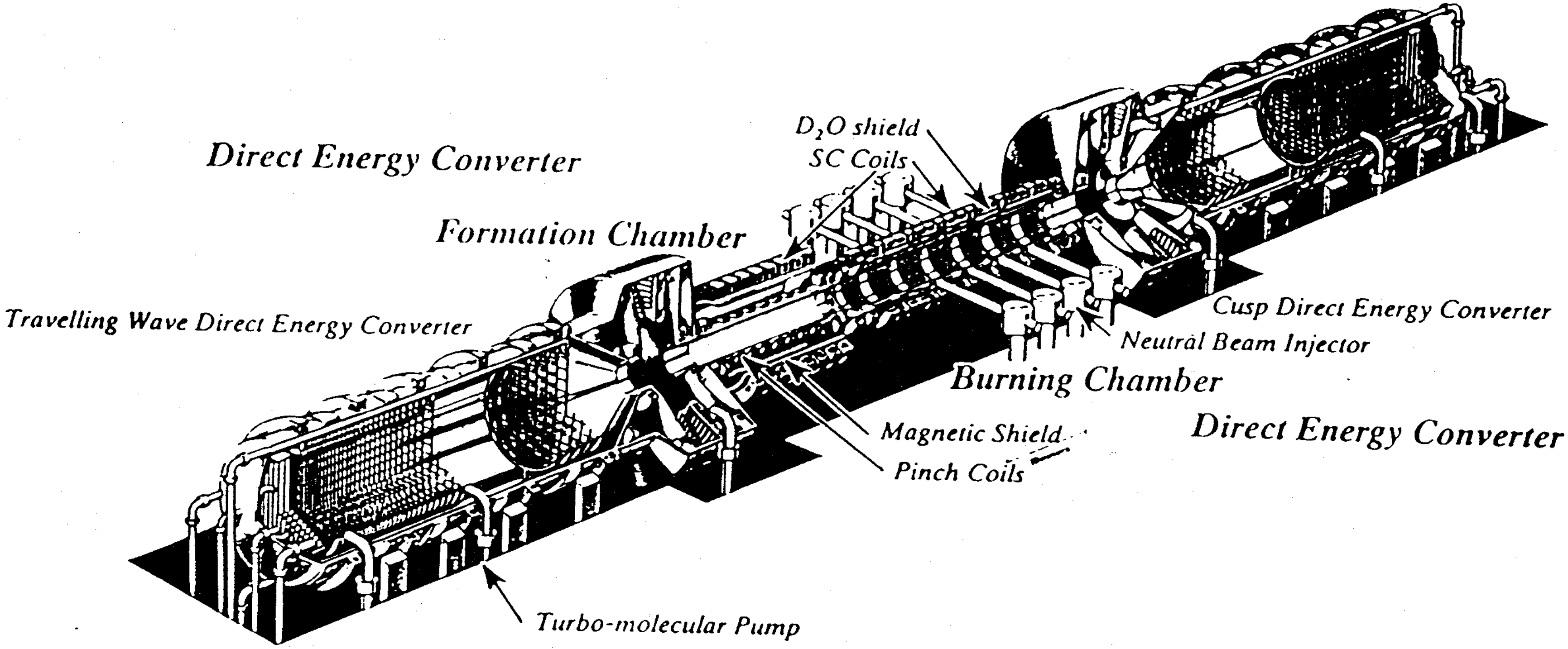
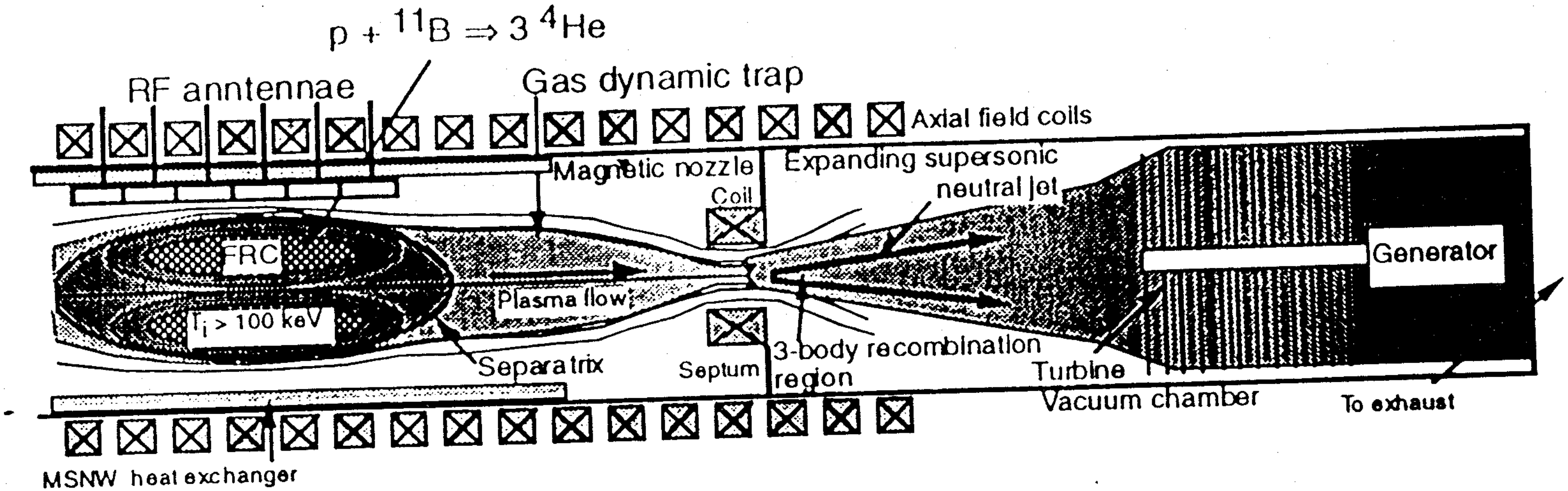


Fig.3: A whole view of the D-^{3}He fueled FRC reactor ARTEMIS-L

Hybrid Fusion Reactor Configuration HBFRC

(S.Cohen et al)



PMI problems eliminated

1) Tritium inventory in PFC
2) Damage and activation of PFC and structural materials by neutrons
3) High PFC sputter erosion rates (0.25 m/burn-yr)
4) High steady-state and intermittent heat fluxes (> 5 MW/m^2) to PFC
5) Very high (> 10^5 MW/m^2) plasma heat fluxes to PFCs during disruptions
6) Material ablation by disruption-generated runaway (> 30 MeV) electrons
7) High forces on structures due to vertical displacement events
8) Difficult *in-vessel* component repair due to complex geometry and radioactivity.

Candidate liquids

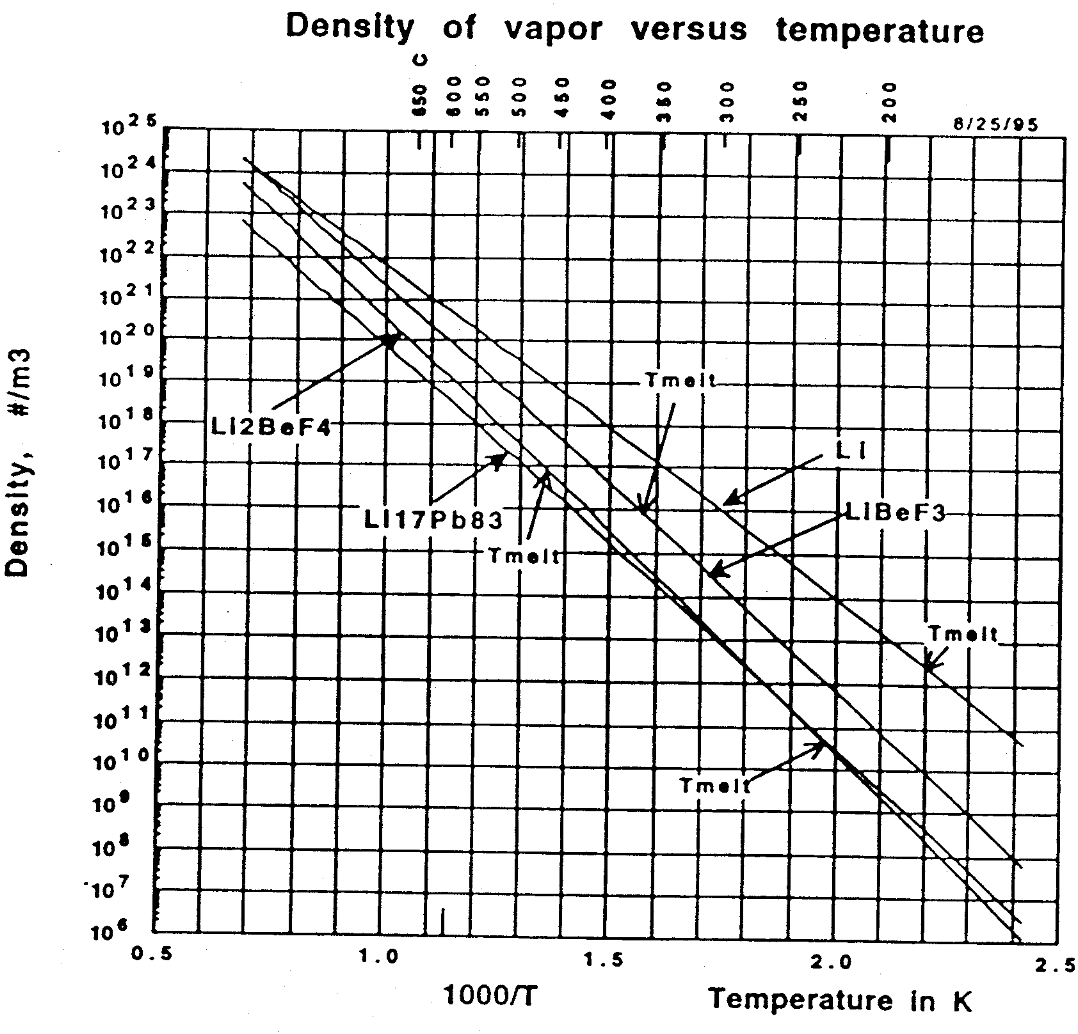


Fig 2

Evaporation rate vs temperature

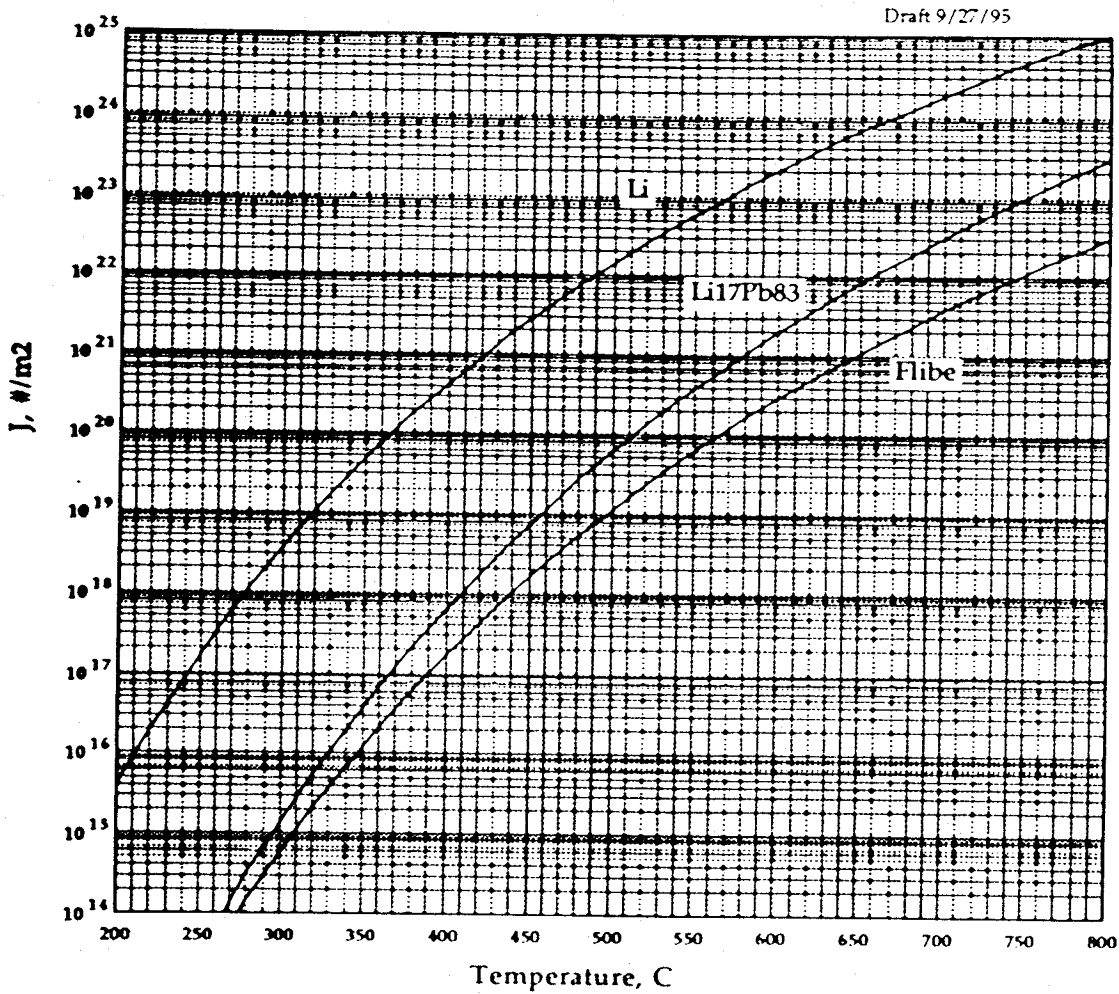
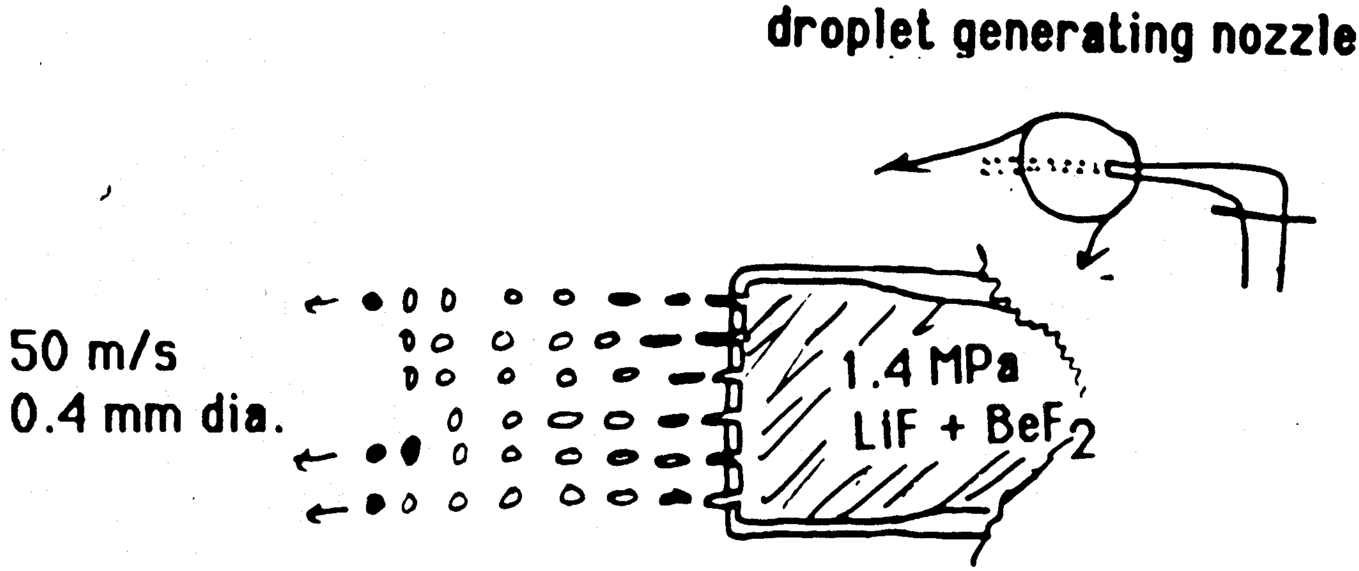
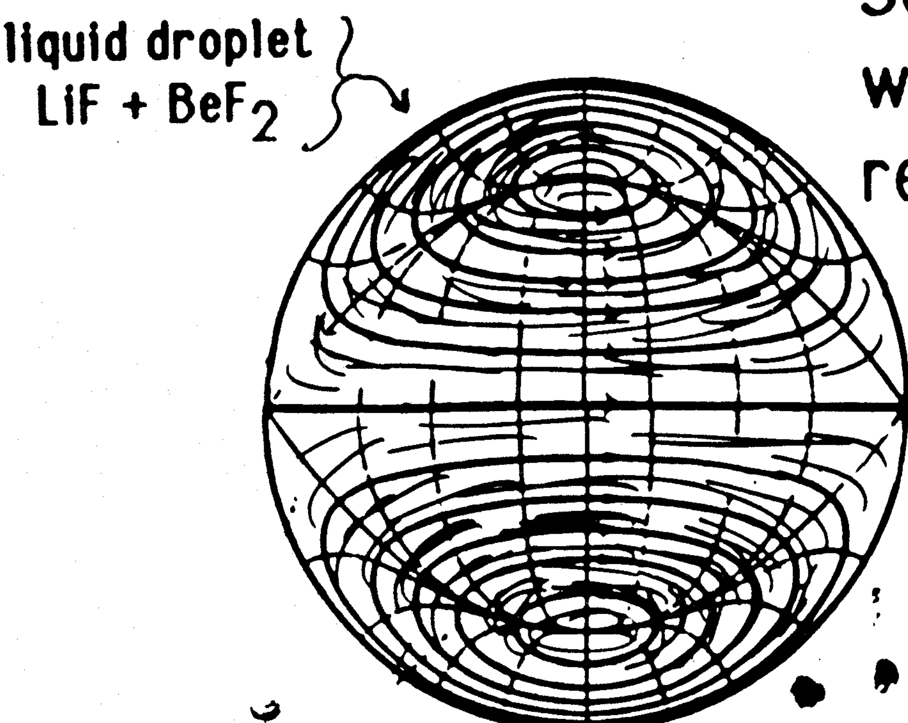


Fig. 3

Internal circulation and oscillations will enhance heat transfer into the droplets by over a factor of 10.*

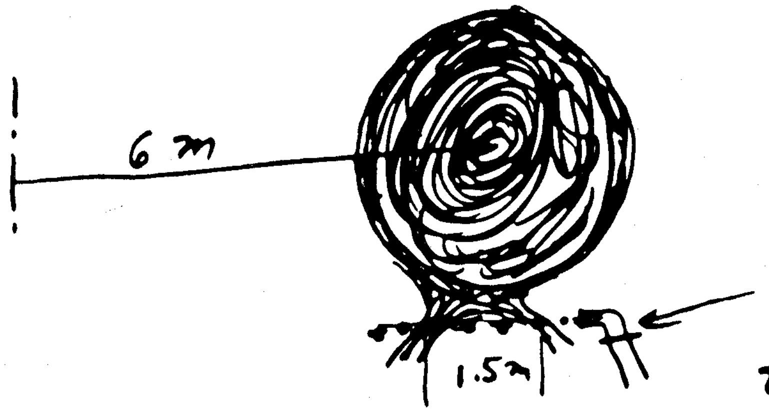


Surface temperature will be reduced which reduces evaporation.



* K. Hijikata, Y. Mori and S. Kawaguchi, "Direct contact condensation of vapor to falling cooled droplets", Int. J. Heat Mass Transfer 27 1631 (1984).

DROPLET HEAT REMOVAL



DROPLET NOZZLE

$$t = \frac{1.5\,m}{50\,m/sec} = 0.03\,Sec$$

$P_f \simeq 3000$ MW

$P_c \sim \underset{\alpha's}{0.2} \times \underset{\uparrow}{\tfrac{1}{2}} \times 3000 \sim 300$ MW

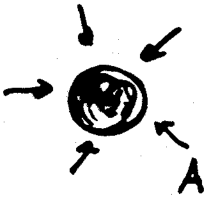
$\tfrac{1}{2}$ RADIATED

AREA $\sim 2\pi\, 6 \times 1.5 \sim 56\,m^2$

$$\frac{P_c}{A} \sim \underline{5.3\,MW/m^2} = \bar{q}$$

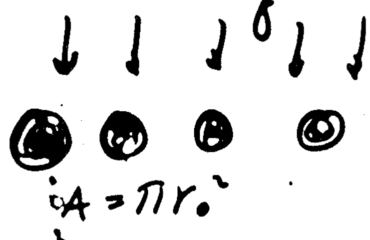
$$\tau = r_0^2 \frac{\rho c}{k} \qquad F_0 = \frac{(T-T_0)k}{q_0 r_0} = t/\tau$$

$T - T_0 = 300$ K



$q_0 \; \frac{W}{m^2}$

$A = 4\pi r_0^2$

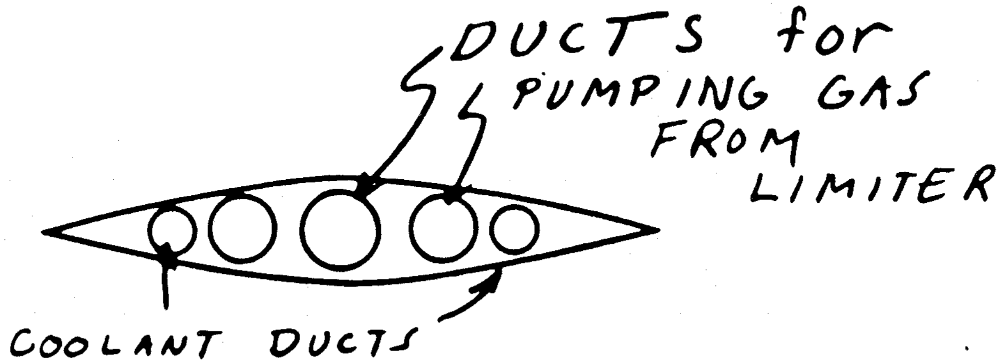


$\bar{q}$

$A = \pi r_0^2$

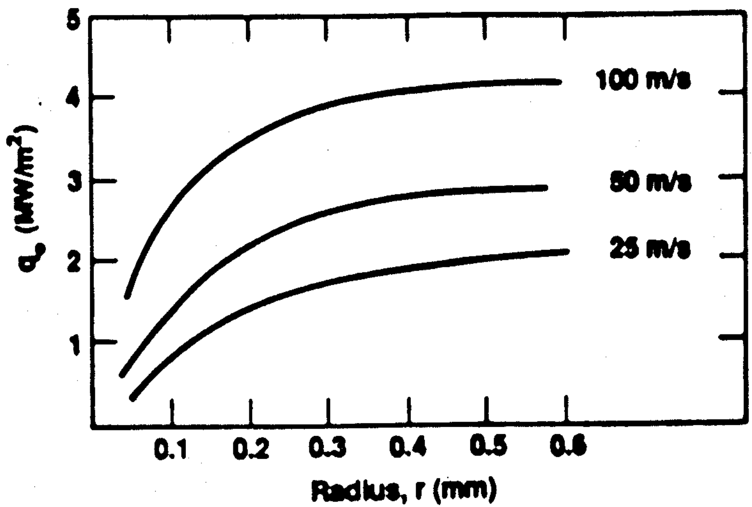
for same average droplet heating

$$\bar{q} = 5.3\,MW/m^2 \Rightarrow q_0 = 1.3\,MW/m^2$$

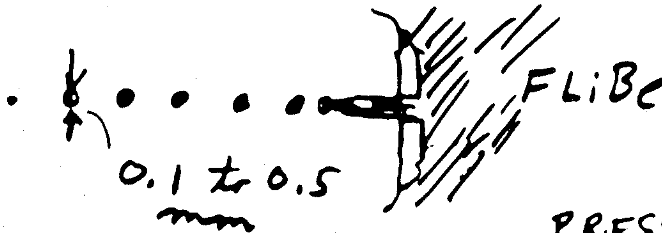


Cross-section of strut that penetrates the moving liquid. ~~The acceleration force, g, is shown for various positions as the fluid element rotates around the circumference of the torus.~~

Uniform heat load on a droplet versus droplet speed. This heat load is indicative of the heat removal capability of a thick droplet stream or sheet.



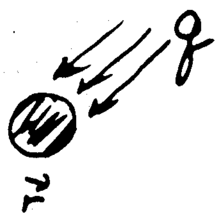
DROPLET GENERATOR



VELOCITY	PRESSURE (C. Hendricks)
40-50 m/sec	200 psi
70-80	400
100	500

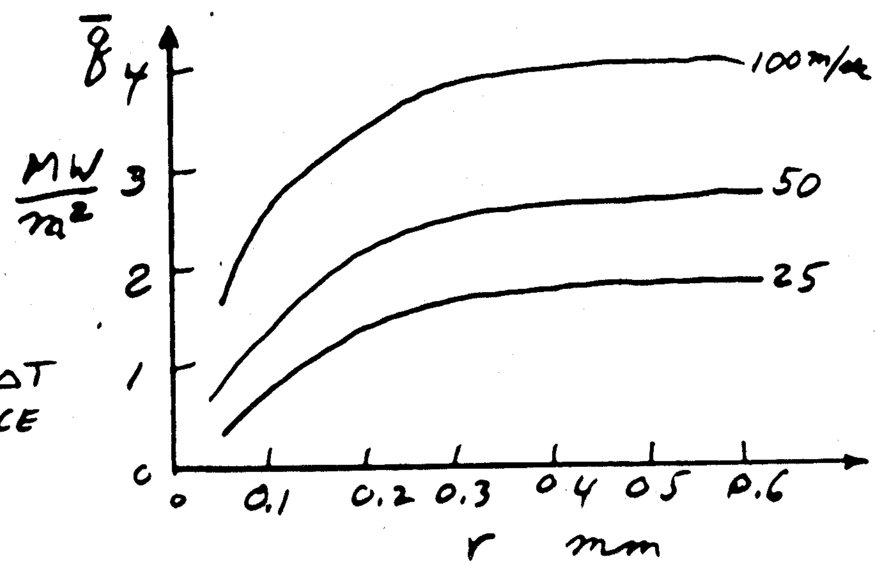
@ 50 m/sec
1.5 m
$\tau \sim 0.03$ sec

HEAT TRANSFER SOLUTIONS

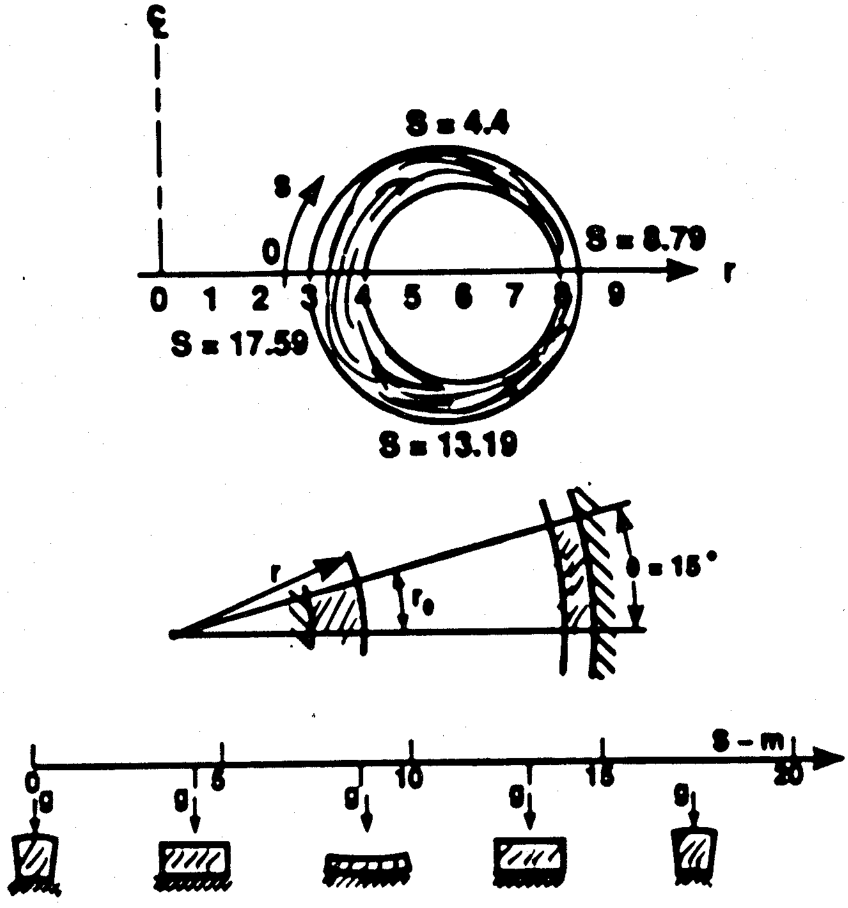


$q \simeq \pi \bar{q}$

300°C ΔT SURFACE



Cross-section of a fluid element as the element is followed around the minor radius.



EVAPORATION

Evaporation parameters for FLiBe.

T (°C)	T (K)	P (Torr)	n (cm^{-3})	J ($cm^{-2}\,s^{-1}$)	Q ($W\,cm^{-2}$)
400	673	2.9×10^{-6}	4.2×10^{10}	7.4×10^{14}	2.5×10^{-4}
450	723	3.2×10^{-5}	4.2×10^{11}	7.7×10^{15}	2.6×10^{-3}
500	773	2.5×10^{-4}	3.1×10^{12}	5.9×10^{16}	2.0×10^{-2}
550	823	1.6×10^{-3}	1.8×10^{13}	3.5×10^{17}	0.12
600	873	7.8×10^{-3}	8.6×10^{13}	1.7×10^{18}	0.58

@ 450°C $J = 7.7 \times 10^{15}$ /cm² sec

AREA $= 2\pi 6 \quad 2\pi 2 \quad = 474\ m^2$

3.7×10^{22} FLiBe MOLECULES/sec

PLASMA VOLUME $= 2\pi 6 \; \pi 2^2 = 474\ m^3$

$\boxed{\text{If impurity Lifetime} = 1\ \text{sec}}$

$n_{FLIBE} = 8\,10^{19} f \ m^{-3}$

f = fraction of evaporated FLiBe penetrating into hot plasma through edge plasma

$n_{DT} = 10^{20}\ m^{-3}$

$n_{FLiBe}/n_{DT} = 0.4 f$

$\boxed{\text{If } n_{FLiBe}/n_{DT} \le 10^{-3}}$

then

$\underline{f \le 0.003}$