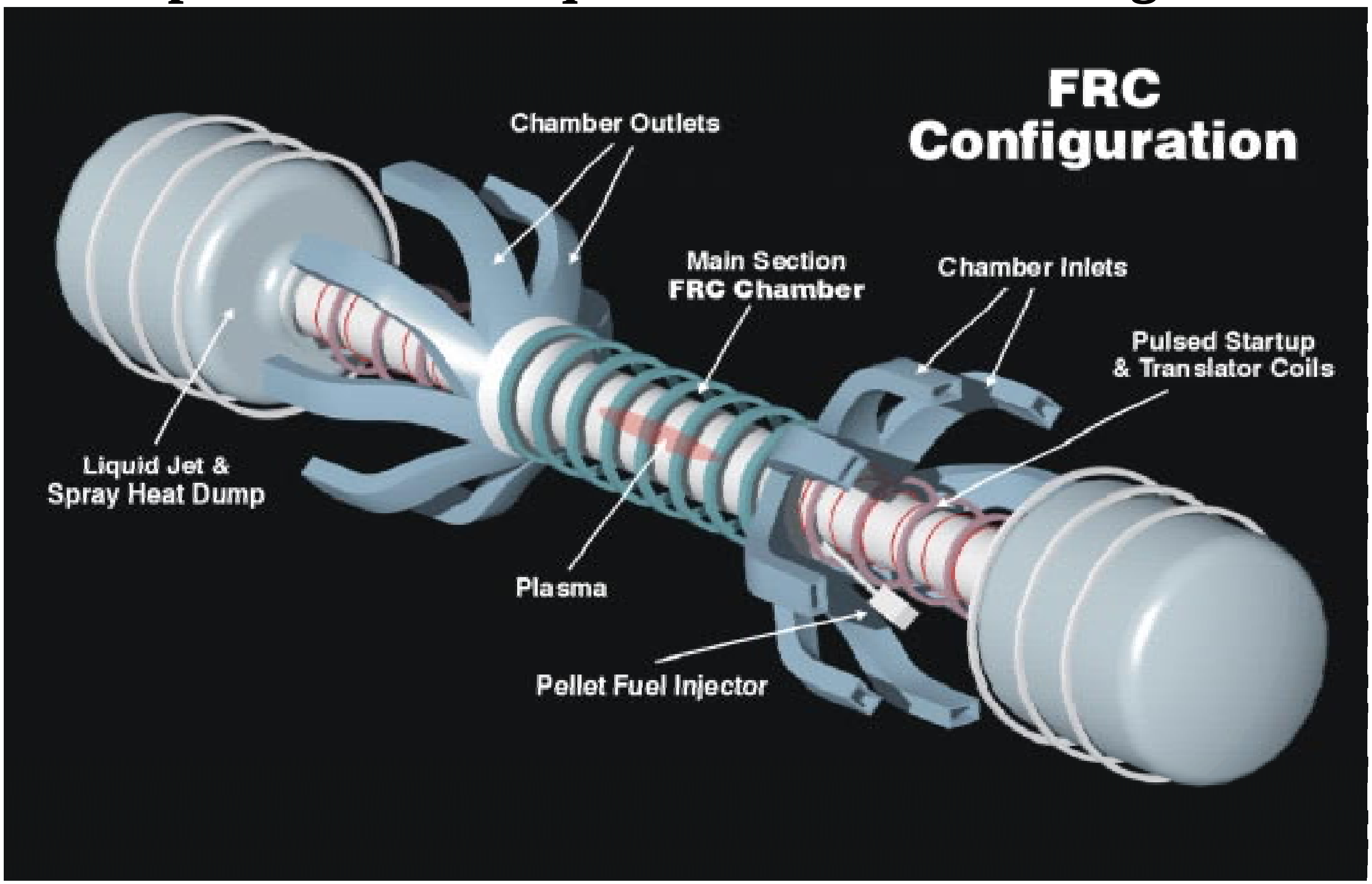
Heat transfer enhancement by liquid droplets

Example of a thick liquid walled-MFE configuration



R. W. Moir **May 10, 2000**
Lawrence Livermore National Laboratory
APEX meeting May 8-12, 2000, ANL

—a paradigm shift—

"The first wall problem"

Strategy #1 solution:

Develop materials that will stand up to the fusion environment

5 MW/m^2 and 20 MWy/m^2 ---> 5 years

Strategy #2 solution:

Engineer around the problem by use of liquid protection so existing materials will work

>20 MW/m^2 and >500 MWy/m^2 ---> 30 years

lower the COE by a large amount?

avoid need for expensive neutron facilities?

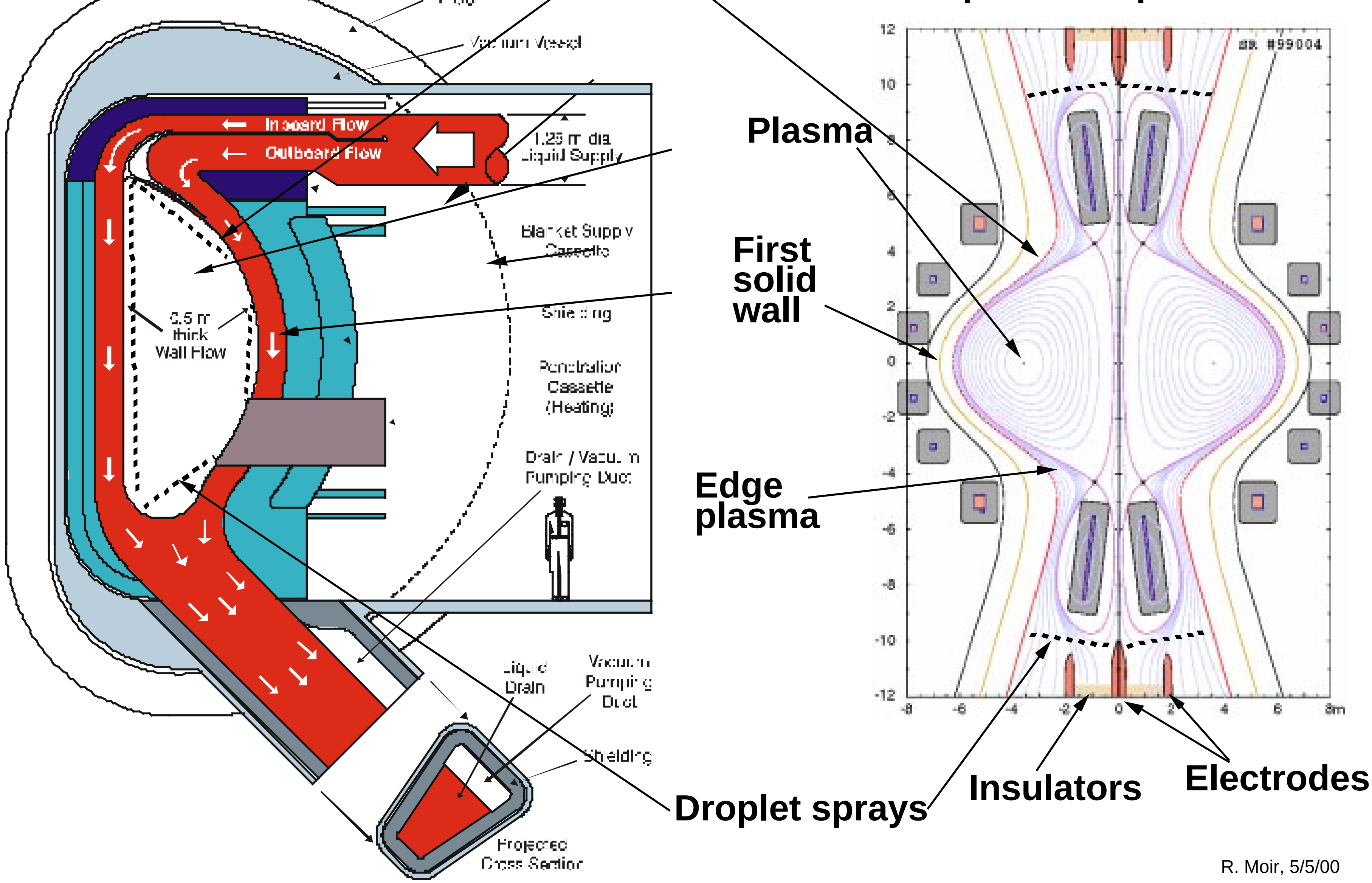
will the edge plasma stop evaporated liquid?

Can droplet sprays cool liquid surfaces?

Liquid wall tokamak

Liquid free surface

Liquid wall spheromak



R. Moir, 5/5/00

Issues unique to liquid wall use depend on device type

Tokamak

- how to get liquid in and out/nozzle design/port needs design/current drive/rad damage to exposed surfaces/ pumping power
- estimate galvanic corrosion rates
- edge plasma/core contamination assessment
- conducting wall design (0.5 m Flibe gap)

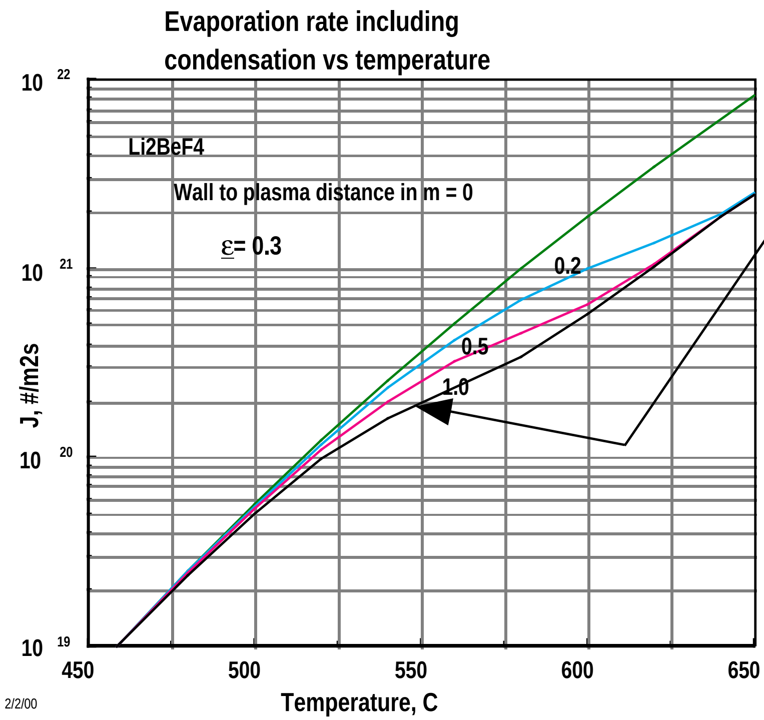
Spheromak

- configuration design/electrodes/insulators/coil locations
- current drive system
- conducting wall design/feedback stabilization (0.5 m Flibe gap)
- edge plasma/core contamination assessment

FRC

- current drive antenna design/estimate galvanic corrosion rates
- edge plasma/core contamination assessment
- conducting wall design if needed (0.5 m Flibe gap)
- "pacman" fueling pulsed coils

Strategies to minimize evaporation from Flibe will need to minimize the surface temperature

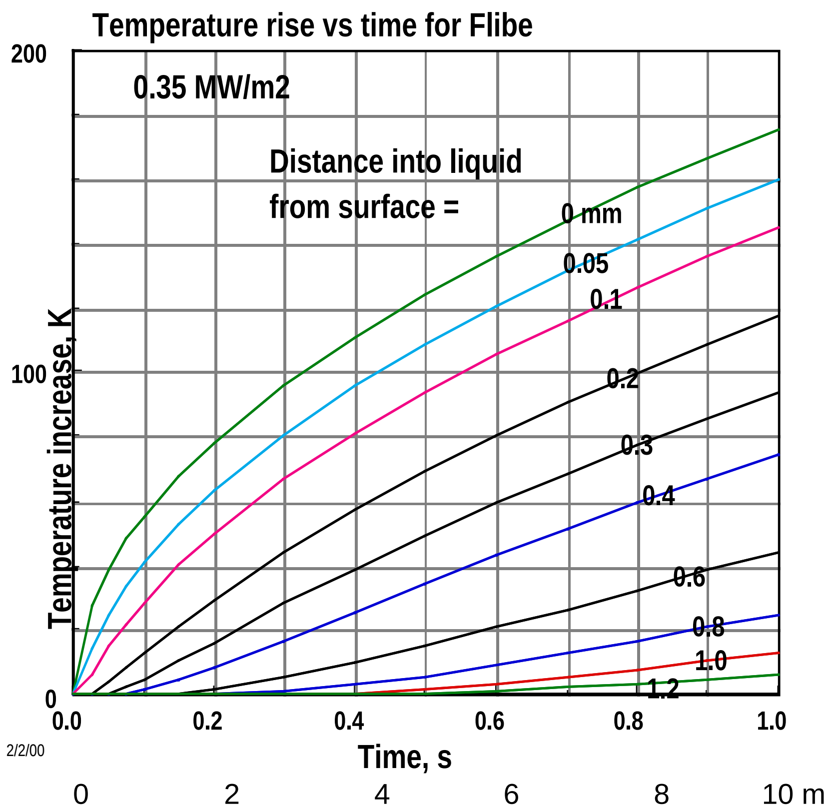


Evaporation is a strong function of temperature even with condensation included.

Evaporation rate at various temperatures for Flibe

Temp C	n BeF_2/m^3	J, x=0 $\#/m^2s$	J, x=0.2 m $\#/m^2s$	J, x=0.5 $\#/m^2s$
500	$3.9x10^{17}$	$5.70x10^{19}$	$5.56x10^{19}$	$5.36x10^{19}$
505	$4.8x10^{17}$	$7.07x10^{19}$	$6.85x10^{19}$	$6.53x10^{19}$
550	$2.4x10^{18}$	$3.66x10^{20}$	$3.14x10^{20}$	$2.56x10^{20}$
555	$2.9x10^{18}$	$4.41x10^{20}$	$3.67x10^{20}$	$2.88x10^{20}$

Surface temperature can be kept near bulk temperature if only a little mixing takes place very near (<<1 mm) the surface.



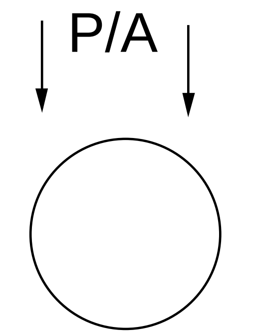
Distance from entrance nozzle along the flow path

Can droplets sprayed onto the surface produce the needed mixing and do so without causing splash?

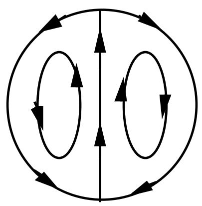
Can effective mixing take place to a depth of 0.2 mm for each 1 m of travel?

Can the surface temperature be kept to <5 °C of the bulk temperature? <25 °C? <50 °C?

Two effects substantially decrease the surface temperature rise on droplets



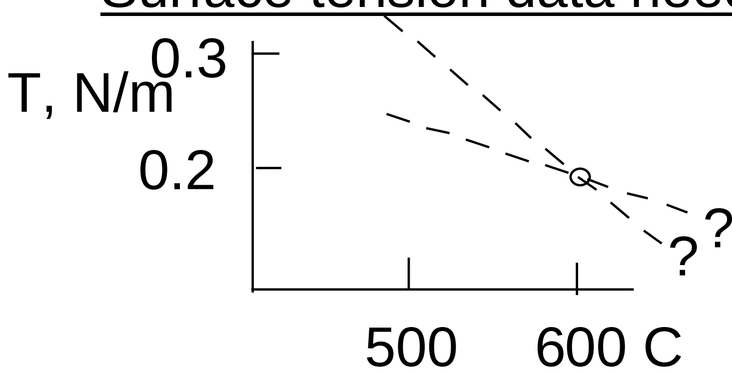
$$T_{rise} = \quad 2\ P/A\ (\alpha\tau/\pi)^{0.5}$$



Manangoni effect convects the hot surface to the cold region and induces internal convection

1-P/A down factor 4 for area averaging
2-Another factor of ??? for convection into the cool interior

Surface tension data needed



90 MW/m^2 predicted Fus. Tech 15 (1989) 674-679.

Evaporation rates will be decreased

Heat transfer enhancement by droplet injection for liquid walls

The idea is to inject droplets so they strike the liquid surface at an acute angle and merge with the flow. The merging process will induce significant vortex motion causing mixing of the cooler interior liquid with the hot surface liquid as shown in the figure below. Droplets in the mm radius range, injected at an angle of ~6° with a velocity of 10 m/s would strike the surface (whose speed is 10 m/s) at a normal speed of 1 m/s and a parallel speed of 9.96 m/s. If the droplet would be absorbed by the liquid without generating outward going droplets, then this 1 m/s speed would contribute to transvers motion of the fluid. In addition, the surface tension will "pull" the liquid from the droplet into the bulk causing additional motion. That is, the surface tension energy is converted to kinetic energy of fluid motion. This motion will be very effective in keeping the surface temperature down, which in turn will lower the evaporation rate.

The problem of droplets striking a liquid surface has been studied extensively. This literature is being researched to determine the conditions for no droplet ejection.

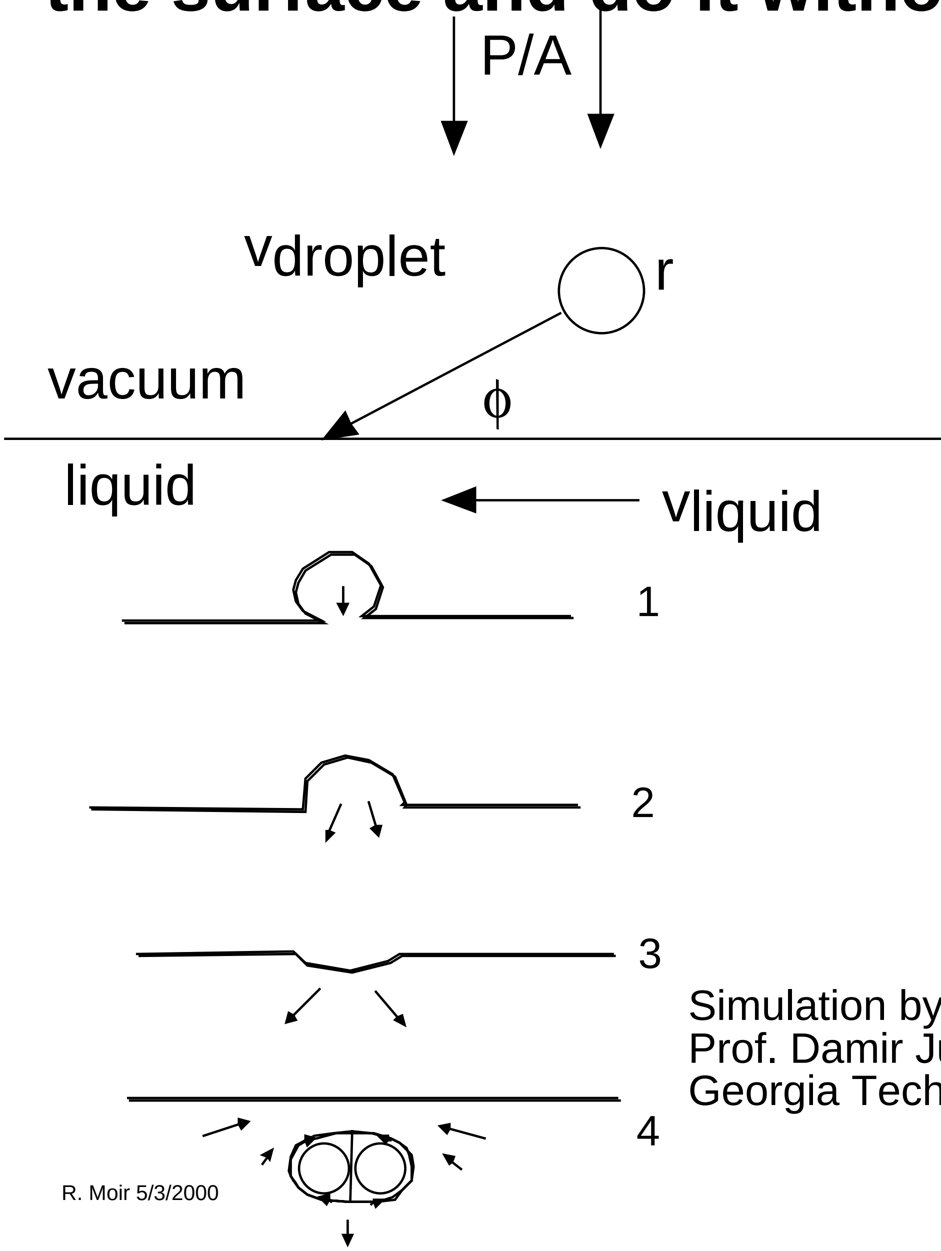
Simple calculations show that even one droplet per square meter per second in the mm radius range is can not be tolerated. Thus we seek a no droplet ejection condition or "no splash" condition.

Table 1

radius	r	0.1 to 10 mm
density	ρ	2000 kg/m3
angle	ϕ	
speed of droplet	$v_{droplet}$	?
surface tension	T	0.2 N/m @ 600 C 33%BeF2 0.35 @ 500 C50% BeF2
gravity	g	
speed of liquid	v_{liquid}	?
viscosity	μ	0.32×10^{-3} Pa.s

<u>Need surface tension measurements versus temperature.</u>

Will droplets injected onto the free surface induce significant convection of cool liquid near the surface and do it without causing splash?



Example of "no splash"

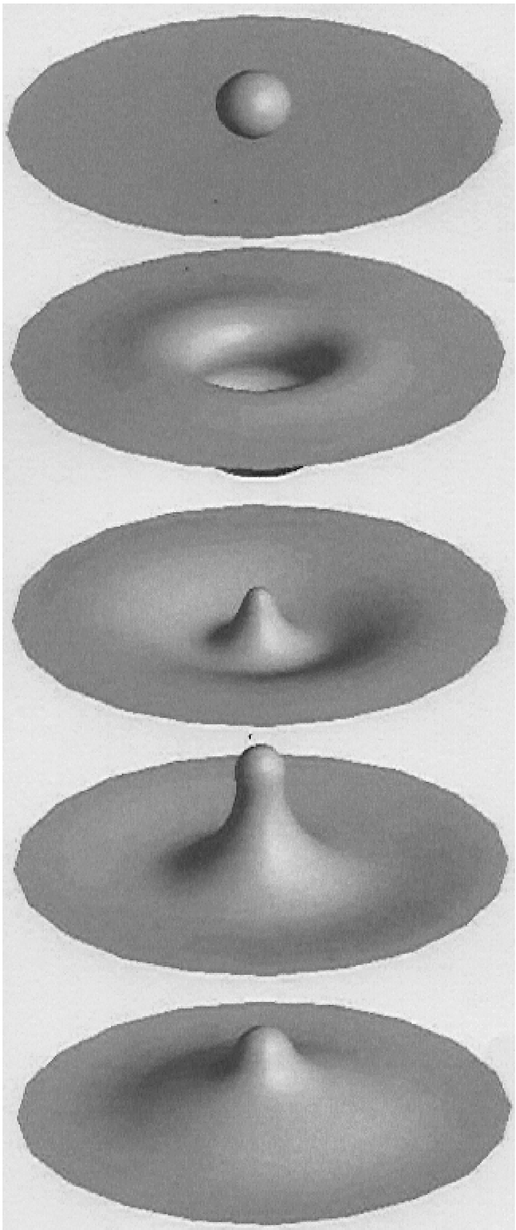
$Re=2vr/\nu=20$

$We=\rho r v^2/\sigma=2$

Simulation by
Prof. Damir Juric
Georgia Tech

R. Moir 5/3/2000

Will droplets sprayed onto a surface lower the average temperature?



Old result:

$$T_{rise} = 2\ P/A\sqrt{\alpha\tau/\pi}$$

τ=s/v; s=distance; v=liquid speed

2-D direct numerical simulations can calculate the temperature from first principles; this is not a turbulence problem.

From Prof. Damir Juric,
Georgia Tech

5/2/2000

Heat transfer solutions for transient heating of Flibe
These are the old results with no convection

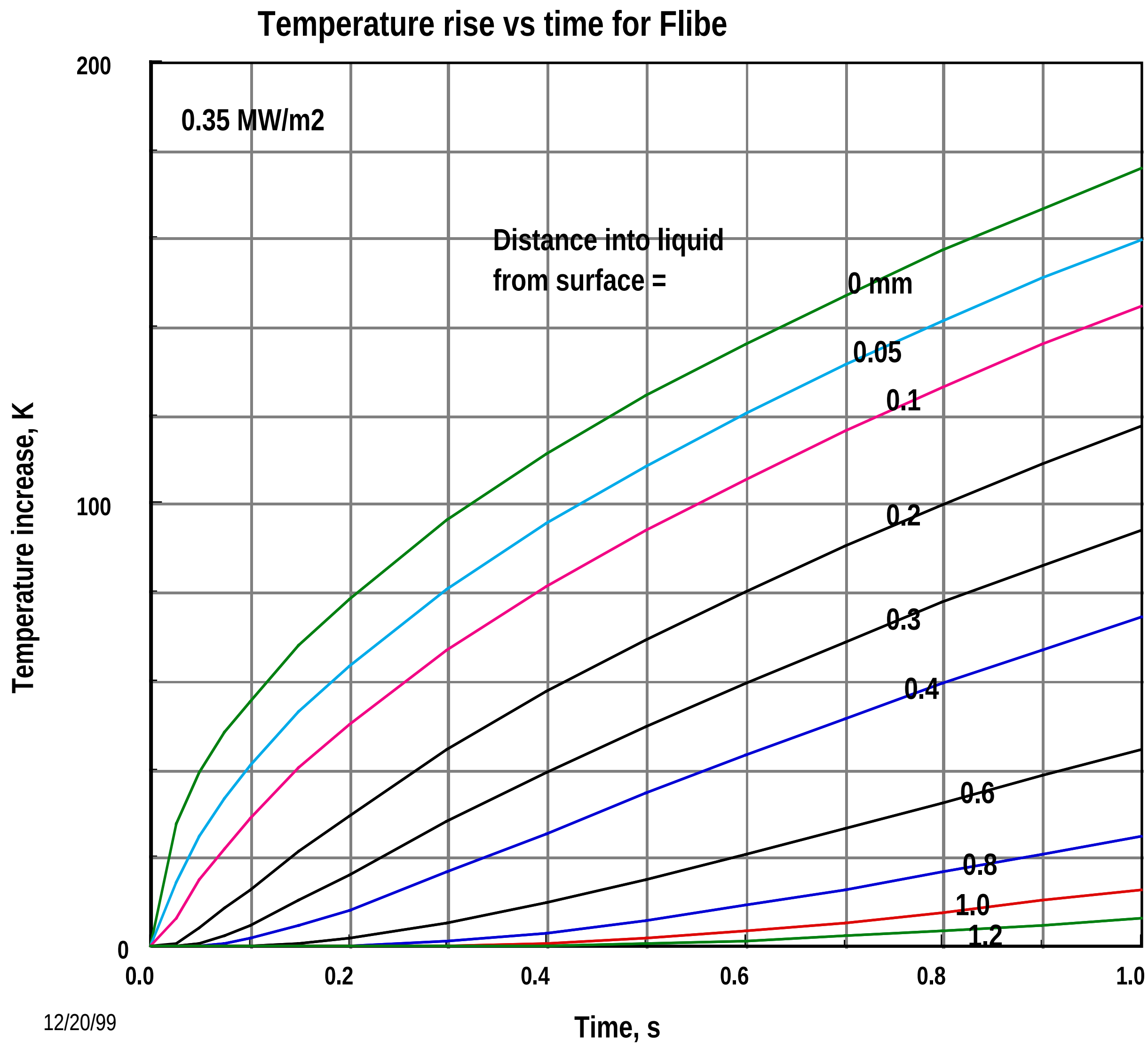
$$\Delta T = 2q\frac{\sqrt{\alpha\tau}}{k}\left[\frac{1}{\sqrt{\pi}}e^{-F_{0x}^{*\,2}} - F_{0x}^{*}\,erfc(F_{0x}^{*})\right]$$ **in interior**

$$\Delta T = \frac{2q}{k}\sqrt{\frac{\alpha\tau}{\pi}}$$ **at surface**

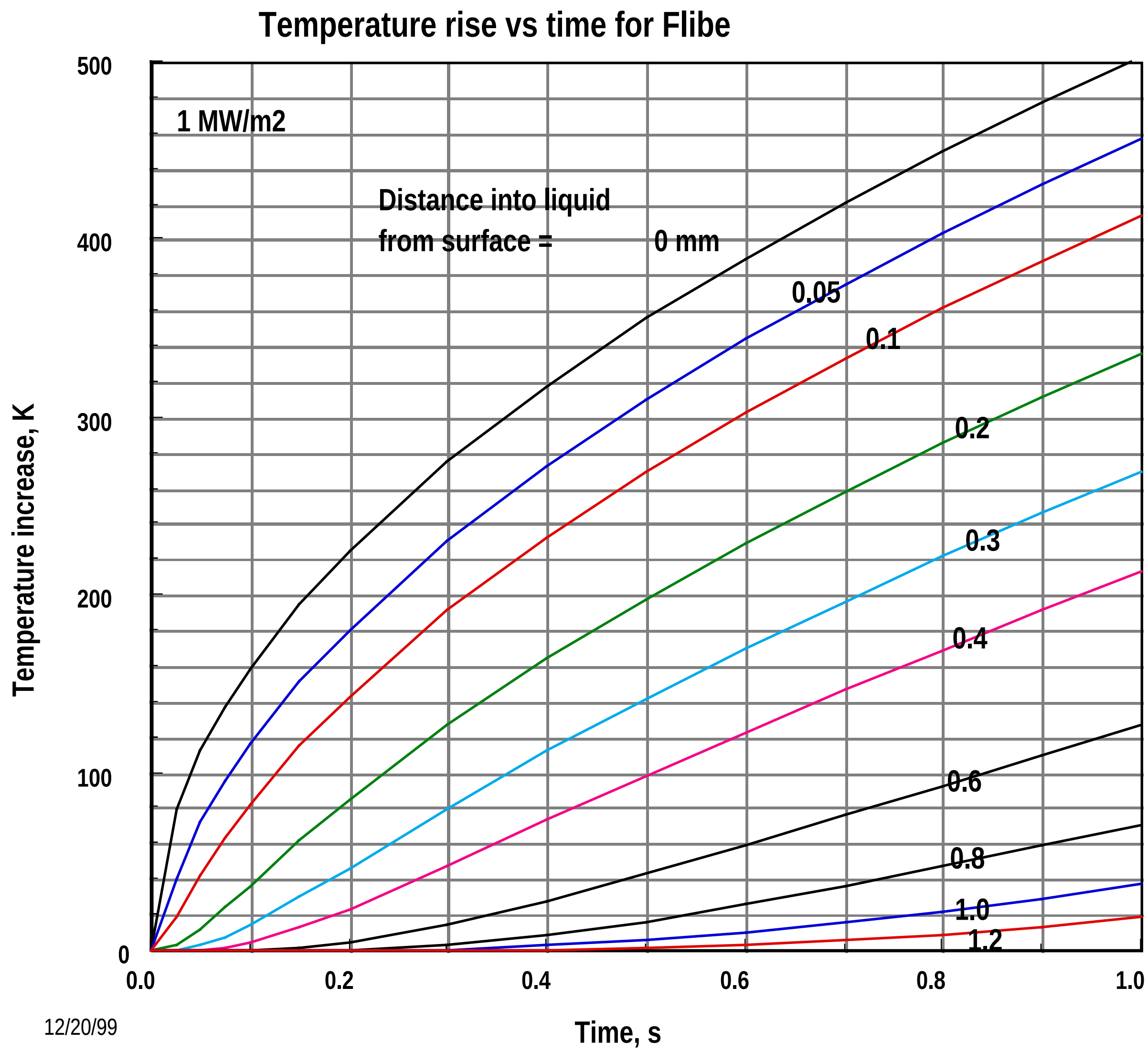
$$\alpha = \frac{k}{\rho c} \qquad F_{0x}^{*} = \frac{x}{2\sqrt{\alpha\tau}}$$

F^* is the normalized distance variable.

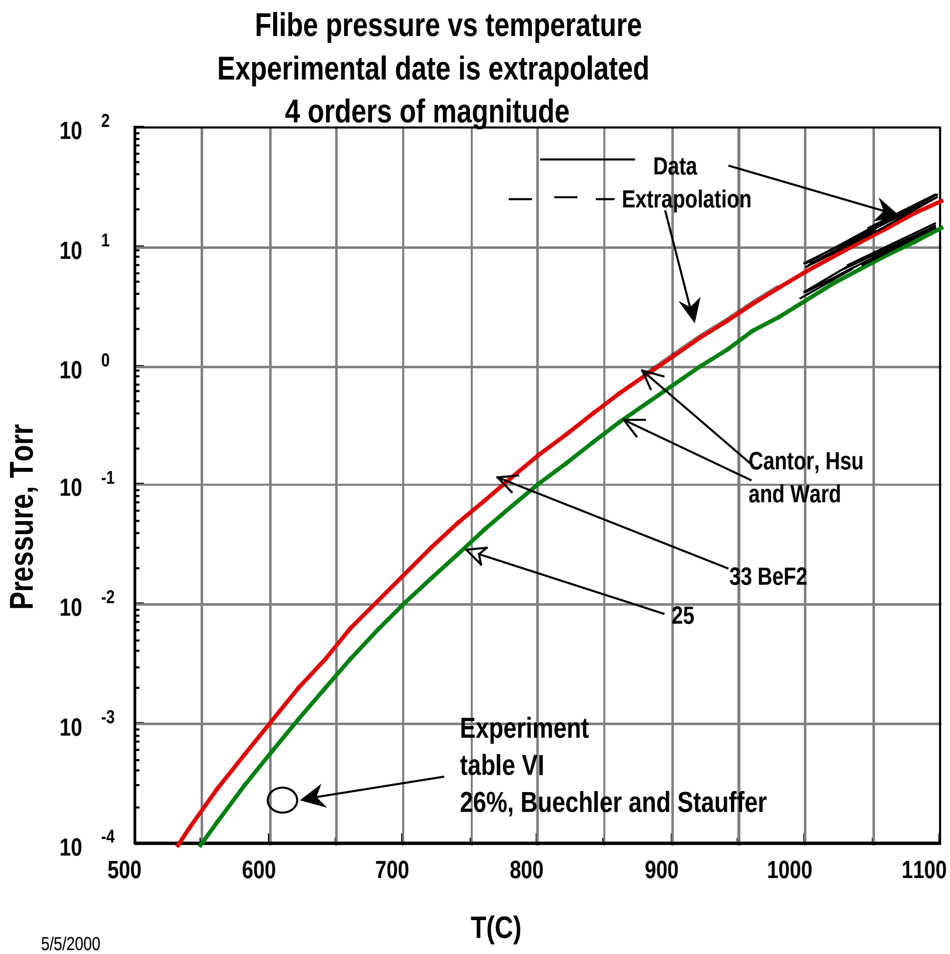
Results with no convection enhancement of heat transfer



Results with no convection enhancement of heat transfer



Flibe vapor pressure is not well known in 500 °C range



Cantor data (ORNL) measured over range of 1000 to 1100 C and extrapolated down to 500 to 600 °C range. Buechler datum at 600 °C is factor of 3 lower.

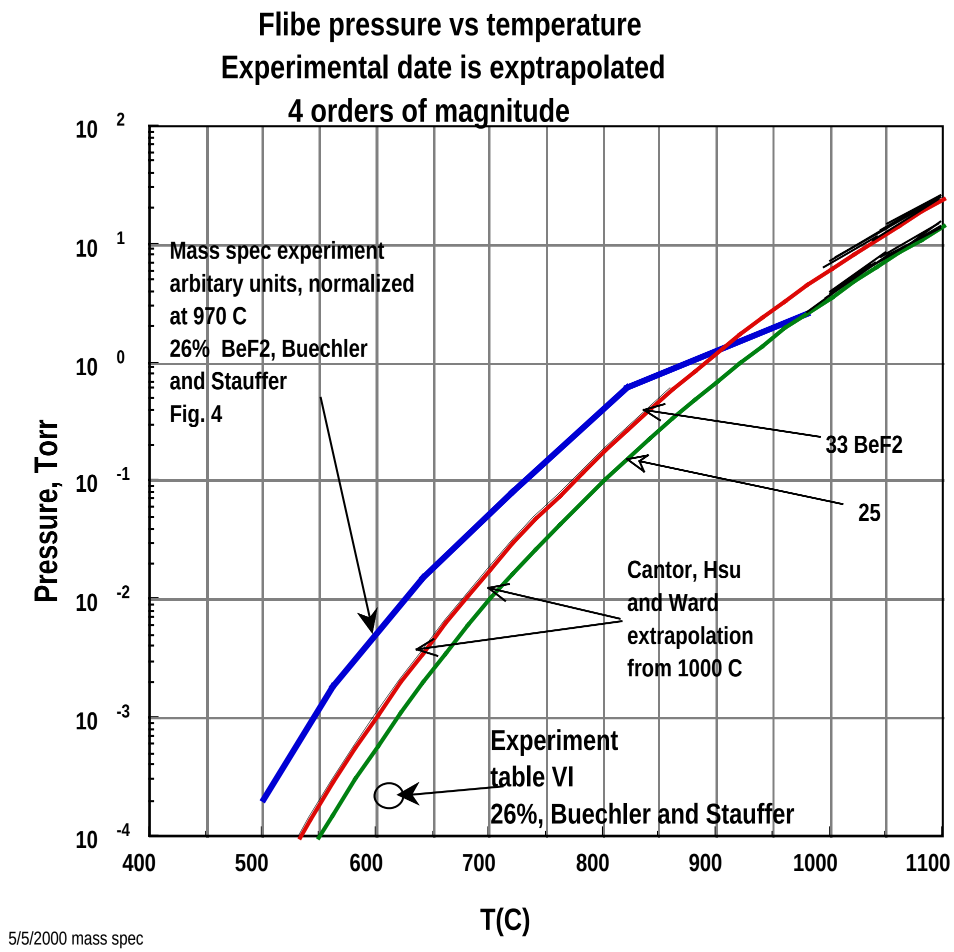
S. Cantor, D. S. Hsu, and W. T. Ward, "Vapor pressures of fluoride melt," Rept., Oak Ridge National Laboratory, Oak Ridge. Tenn, ORNL-3913, ppl 24-26 (1965).

A. Buechler and J. L Stauffer, "Vaporization in the lithium fluoride-beryllium fluoride system," IAEA Symposium on

Input from Prof. Per Peterson appreciated.

Vapor pressure measurements are needed

Flibe vapor pressure is not well known in 500 °C range



Cantor data (ORNL) measured over range of 1000 to 1100 C and extrapolated down to 500 to 600 °C range. Buechler mass spec data normalized at 970 C is high by factor of 4 in 500 C range.

S. Cantor, D. S. Hsu, and W. T. Ward, "Vapor pressures of fluoride melt," Rept., Oak Ridge National Laboratory, Oak Ridge. Tenn, ORNL-3913, ppl 24-26 (1965).

A. Buechler and J. L Stauffer, "Vaporization in the lithium fluoride-beryllium fluoride system," IAEA Symposium on

Recommendation: get second opinion of a chemist and make new vapor pressure measurements.

Conclusions

- **Droplets might be able to enhance surface convection of cool Flibe especially when Marangoni convection is included thus lowering evaporations rates.**

- **Numerical simulations are needed and surface tension data for Flibe are needed.**

- **Measurements of Flibe vapor pressure at 500 to 600 °C are needed.**

Conclusions

- The FRC is a “low recycle” configuration; divertor located far away.

- The spheromak is intermediate

- The tokamak is a “high recycle” configuration; divertor close coupled.