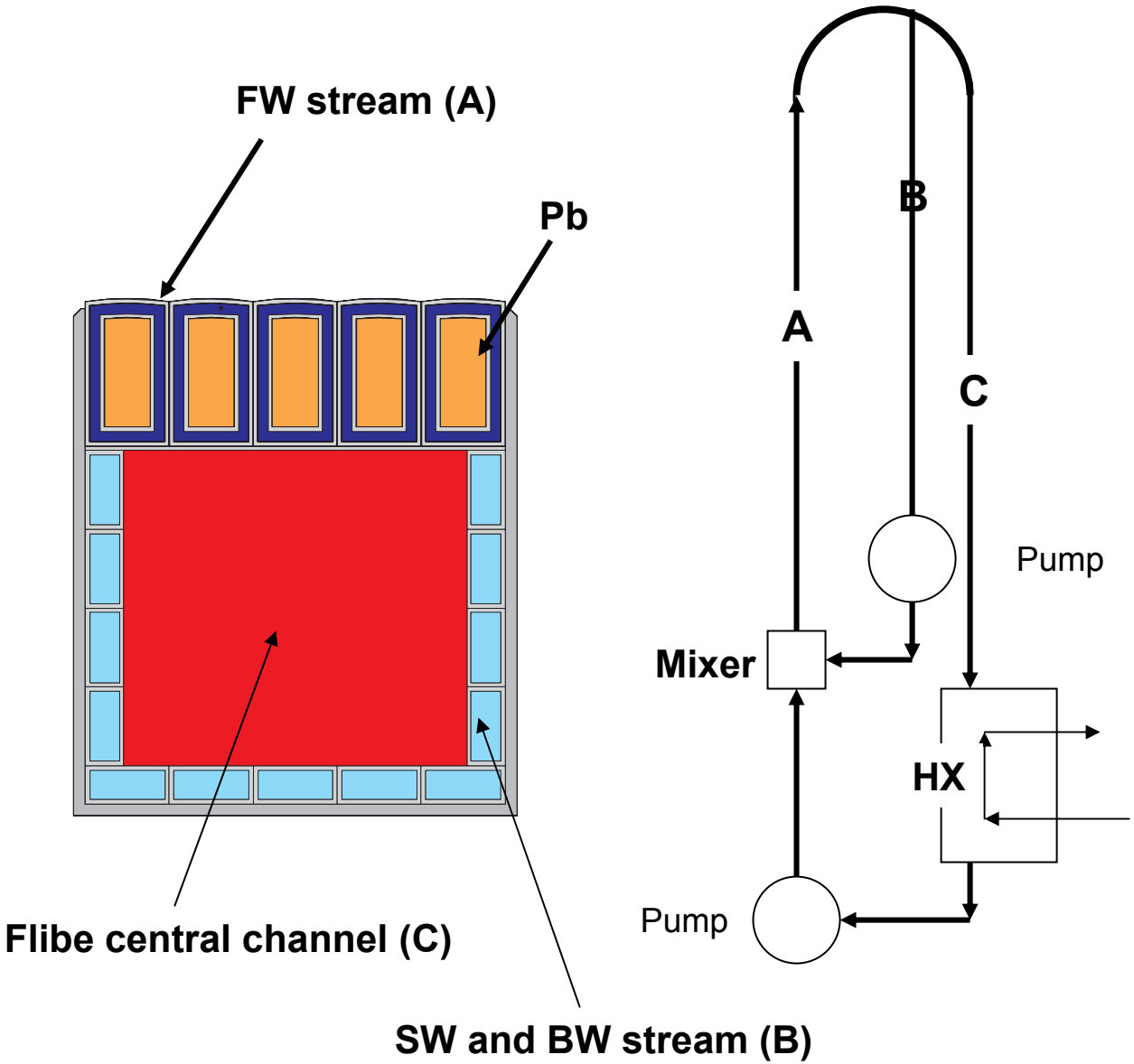
THERMAL HYDRAULICS DESIGN OF THE RE-CIRCULATING FLIBE BLANKET

Recirculating Flibe Blanket Design — APEX-Task IV team
Parametric assessment — C. Wong, GA
MHD effects assessment — S. Smolentsev, UCLA
Heat transfer with MHD — E. Mogahed, UW

For the APEX Task IV Team

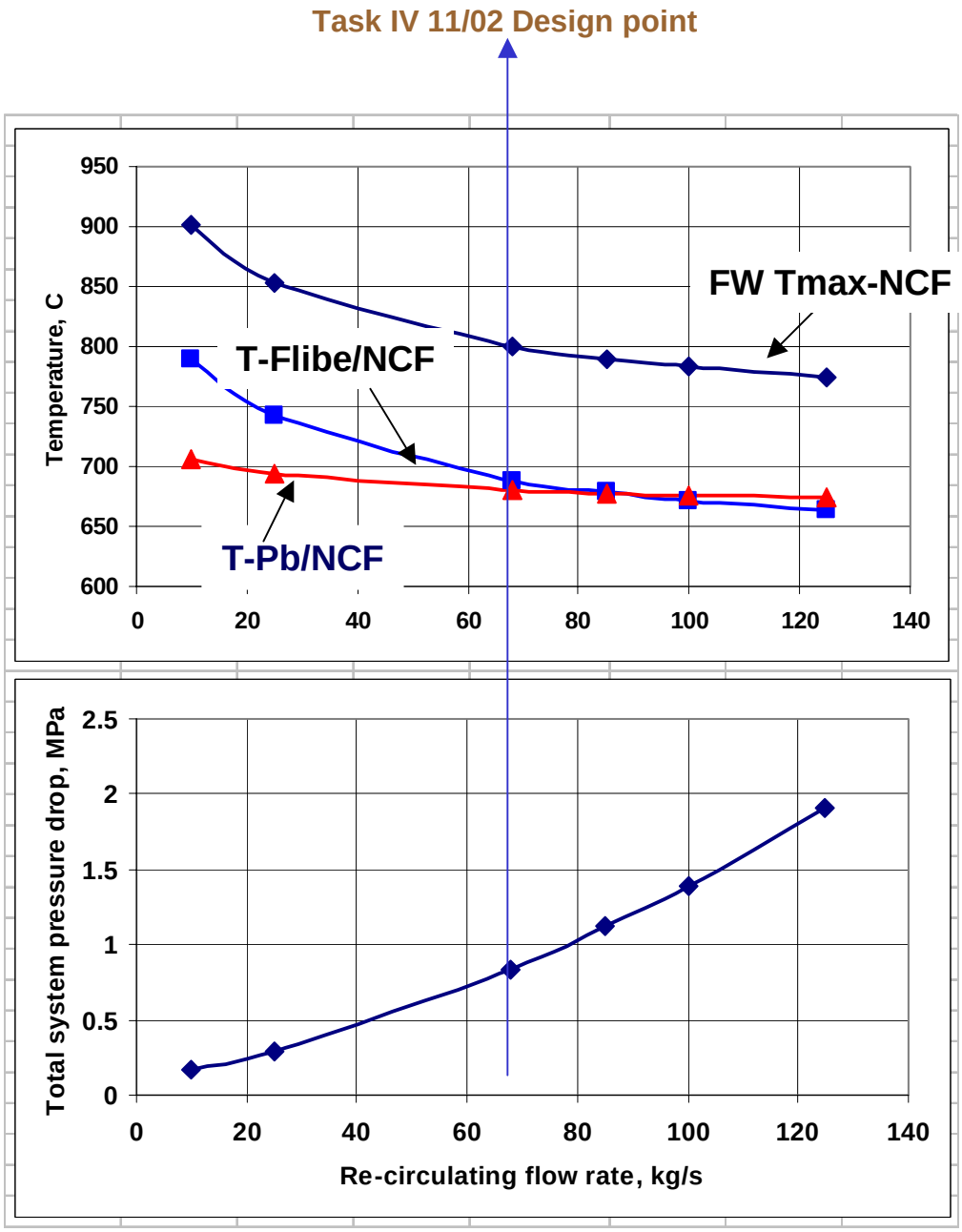
2003 US-Japan Workshop on
High Heat Flux Components and Plasma Surface Interactions for Next Fusion Devices
& High Power Density Devices and Designs
Manresa Hotel, Port Townsend, Washington, USA, July 28-31, 2003

Workshop Agenda


FW stream (A)
Pb
Flibe central channel (C)
SW and BW stream (B)
A
B
C
Pump
Mixer
HX
Pump

KEY PARAMETERS CAN BE CONTROLLED BY THE RE-CIRCULATION MASS FLOW RATE

(Tin=500 C, Tout=683 C)



ΔP, MPa

Re-circulating flow rate, kg/s

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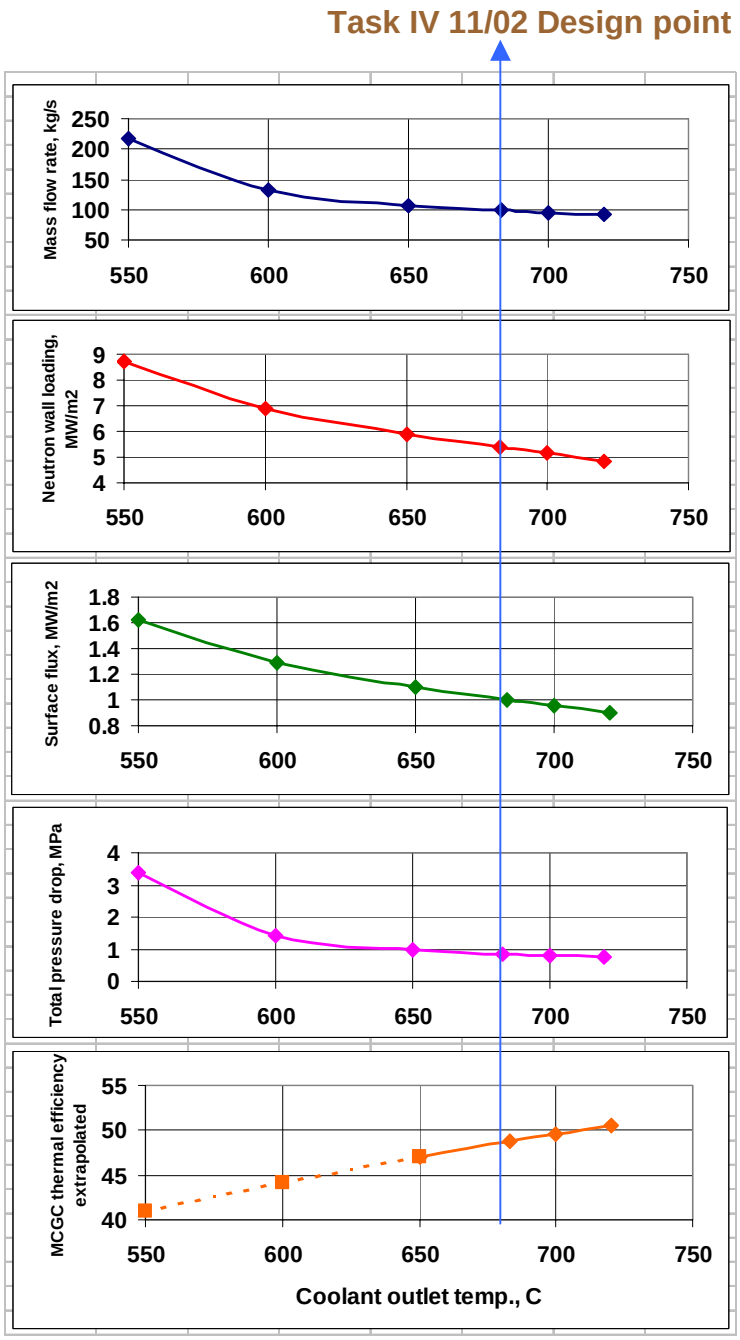
VARIATIONS WITH INCREASE OF T_{OUT} (C) WITH SELECTED GEOMETRY AND TMAX-NCF < 800 C

(Higher Wall Loading at a Cost)



Outboard FW mass flow rate, kg/s, decreases

Neutron wall loading MW/m^2, decreases

Surface heat flux MW/m^2, decreases

Total System ΔP, MPa, decreases

MCGC η_{th}, % Increases
(Data extrapolated from P. Peterson's paper)

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INBOARD AND OUTBOARD THERMAL HYDRAULICS PARAMETERS

Table 1. (October 23rd 2002)	Inboard	Outboard
Number of module per sector	5	9
Mid-plane module width, m	0.3	0.3
Input power:		
Module power, MW	8.17	13.33
First wall including heat flux, MW	4.32	7
Side+back wall, MW	0.88	1.45
Central Flibe column, MW	2.97	4.88
FW & Pb zone inlet/mid-plane /outlet (top)		
FW Heat flux, MW/m^2	0.55/0.69/0.55	0.8/1/0.8
Max. neutron wall loading, MW/m^2	1.56/2.33/1.56	2.8/5.38/2.8
Neutron poloidal peaking factor to average	0.94	1.42
FW mass flow rate, kg/s	55.76	98.6
Coolant flow area, m^2	0.00781	0.00781
Tcoolant-bulk, ˚C	584/600/616	586/601/616
Flibe velocity, m/s	3.58/3.59/3.61	6.33/6.36/6.38
Hydraulic diameter, cm	1.54	1.54
Re	8576/9480/10441	15378/16851/18407
h, W/m^{2}K	7411/7871/8340	12483/13187/13905
FW NCF/Flibe Tinterface, ˚C	664/698/687	674/688/679
FW Tmax, ˚C	716/772/739	733/800/790
Pressure drop, MPa	0.28	0.75
Mid-plane Pb wall NCF/Flibe interface T, ˚C	632	635
Mid-plane Pb wall NCF/Pb interface T, ˚C	657	680
Mid-plane Pb max, ˚C	939	1185
Side and back wall inlet/mid-plane /outlet (top)		
Mass flow rate, kg/s	37	68
Tcoolant-bulk, ˚C	616/621/626	616/620 /625
Mid-plane Flibe velocity, m/s	1.49	2.75
Hydraulic diameter, cm	2.61	2.61
Mid-plane Re	7392	13505
Mid-plane h,W/m^{2}K	3578	6165
Pressure drop, MPa	0.029	0.086
Central Flibe zone inlet/mid-plane /outlet (top)		
Mass flow rate, kg/s	18.8	30.6
Tcoolant-bulk, ˚C	616/649/683	616/649 /683
Mid-plane Flibe velocity, m/s	0.2	0.33
Volume flow rate, m^3/s	0.0097	0.0159
Estimated residence time, s	40	24
Hydraulic diameter, cm	21.84	21.84
Mid-plane Re	9745	15869
Mid-plane h, W/m^{2}K	522	810
Pressure drop, MPa	0.000059	0.000140
Total module FW/blanket pressure drop, MPa	0.306	0.836

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MHD ISSUES

- Effect of a magnetic field on turbulence
- Effect of a magnetic field on heat transfer
- MHD pressure drop
- Natural convection + MHD

FLOWS

- **Front channel**
- **Side channel**
- **Central channel**

Flows are treated as fully developed.
Some effects were not considered:

- **entry/exit effects**
- **cross-sectional variations**
- **changes of the flow direction**
- **magnetic field variations**

INBOARD:	B=7.8 T
OUTBOARD:	B=4.3 T

Effect of a magnetic field on turbulence

- $Ha/Re > (Ha/Re)_{cr} = 0.008 \rightarrow$ turbulence suppression (ins.walls)
- "K-epsilon" model (ins.walls)

INBOARD

Flow	Ha/Re	Suppression
Front channel	0.0017	insignificant
Side channel	0.002	insignificant
Central channel	0.018	laminar flow

OUTBOARD

Flow	Ha/Re	Suppression
Front channel	0.0005	insignificant
Side channel	0.0008	insignificant
Central channel	0.006	almost laminar

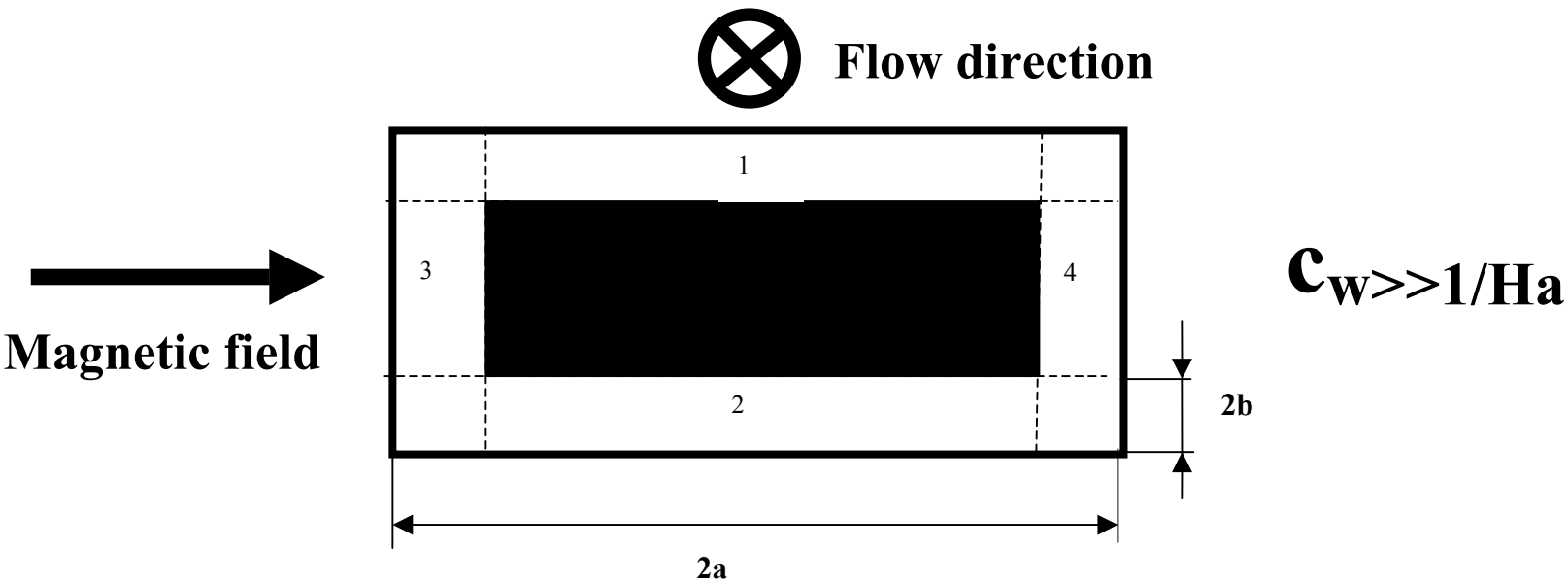
Effect of a magnetic field on heat transfer

$$Nu/Nu_0 = (1 - 1.2\ N_D)$$
$$N_D = Ha_D^2/Re_D = \sigma D B_0^2/\rho U_0$$

$N_D \ll 1 \rightarrow$ EFFECT INSIGNIFICANT

Note: conducting walls ?

MHD pressure drop



Schematic for the **front channel** flow:

1 - front sub-channel
2 - back sub-channel
3 , 4 - side sub-channels

MHD pressure drop

$$(-\frac{dP}{dx})_{MHD} = (-\frac{dP}{dx})_L + (-\frac{dP}{dx})_{Ha} + (-\frac{dP}{dx})_S$$

- Analytical solution for Ha>>1:

$$(-\frac{dP}{dx})_{MHD} = \sigma U_0 B_0^2 \frac{1}{1 - \frac{1}{Ha} - \frac{2.4}{Ha^{3/2}\beta}}$$

- 2-D computer code for any Ha

MHD pressure drop

$$(-\frac{dP}{dx})_{MHD} = K \times U_0$$

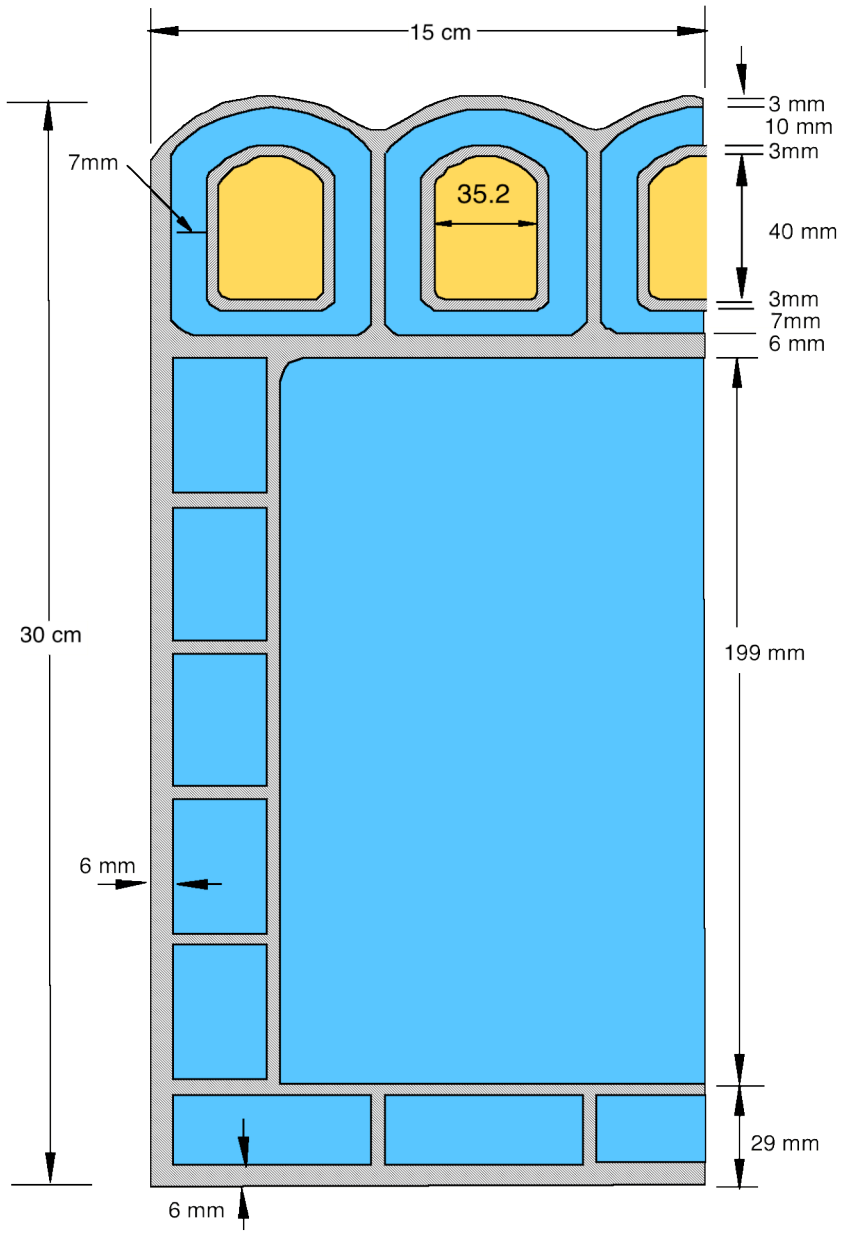
	INBOARD	OUTBOARD
Front/back sub-channel		
K, analytical / K, code	12490 / **13682**	6634 / **6979**
Side sub-channels		
K, analytical / K, code	16631 / **15213**	17352 / **7525**

CONCLUSIONS

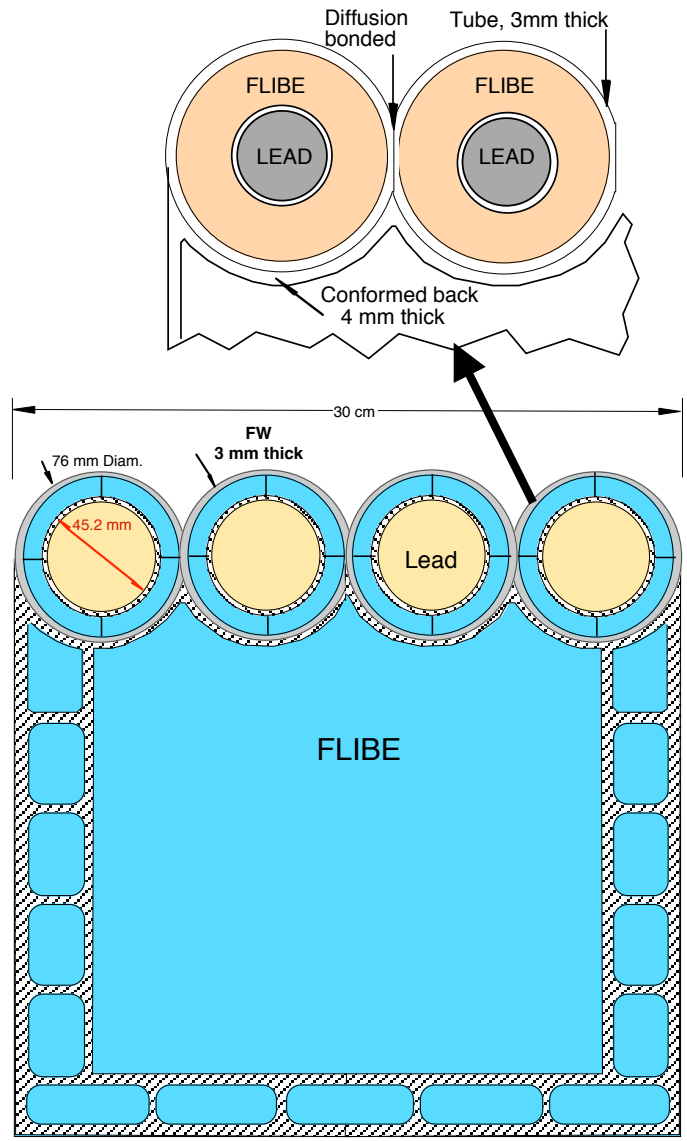
- Turbulence suppression in the flow through the side and front channels is insignificant;
- In the central channel, flow is fully laminarized;
- MHD effect on heat transfer in the flow through the front channels is insignificant;
- Formulas for MHD pressure drop have been obtained for both IB and OB.

FW Thermal Hydraulics Analysis

- Considered two options with circular and rectangular FW tubes
- Assessed improvement resulting from using eccentric Pb tubes in the FW channels
- Optimized FW channel dimensions to maintain uniform pressure drop (including MHD pressure drop) and uniform Flibe temperature
- Determined FW thermal hydraulics parameters (pressure drop, velocities, temperatures for the reference rectangular FW channels



NCF/FLIBE FW/Blanket Concept



Option with Circular FW Tubes

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Formulas, parameters, and data used

$Nu = 0.0118\ Pr^{0.3}\ Re^{0.9}$

For $Pr>20$

The Blasius friction coefficient,
$f = 0.3164/Re^{0.25}$

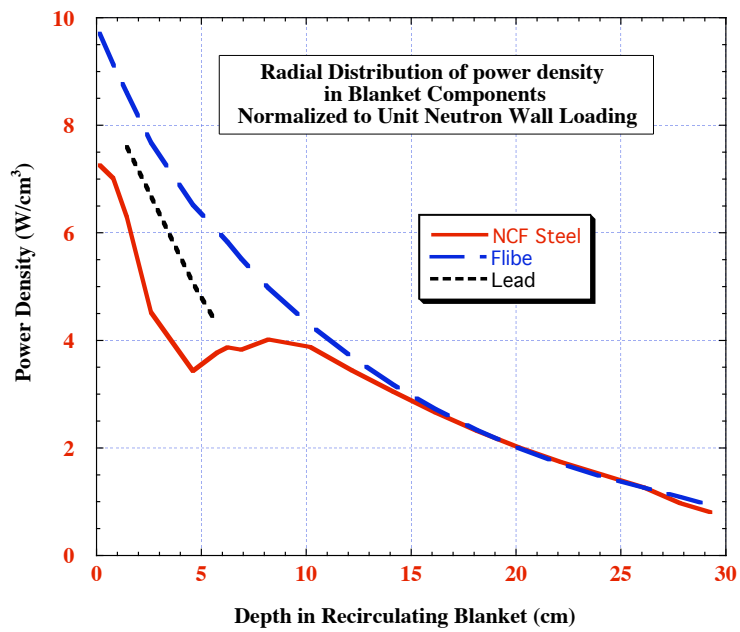
Pressure drop in a vertically moving fluid:
$\Delta P = \rho v^2/2 + f \rho L\ v^2/2d$

where:

Nu is the Nusselt number,
Pr is the Prandtl number,
Re is the Reynolds number,
ρ is the fluid density,
v is the coolant velocity,
d is the coolant tube hydraulic diameter, and
L is the coolant tube length.

<u>Flibe properties at *600 °C*</u>

density = 2120 kg/m^3
thermal conductivity = 1 W/mK
heat capacity = 2380 J/kg K
kinematics viscosity = 5.48e-6 m^2/s



- Nuclear heating profiles used in analysis
- Peak neutron wall loading = 5.45 MW/m^2
- Peak surface heat flux = 1 MW/m^2
- Average OB neutron wall loading = 4.61 MW/m^2
- Average IB neutron wall loading = 2.80 MW/m^2
- Average OB surface heat flux = 0.95 MW/m^2
- Average IB surface heat flux = 0.90 MW/m^2

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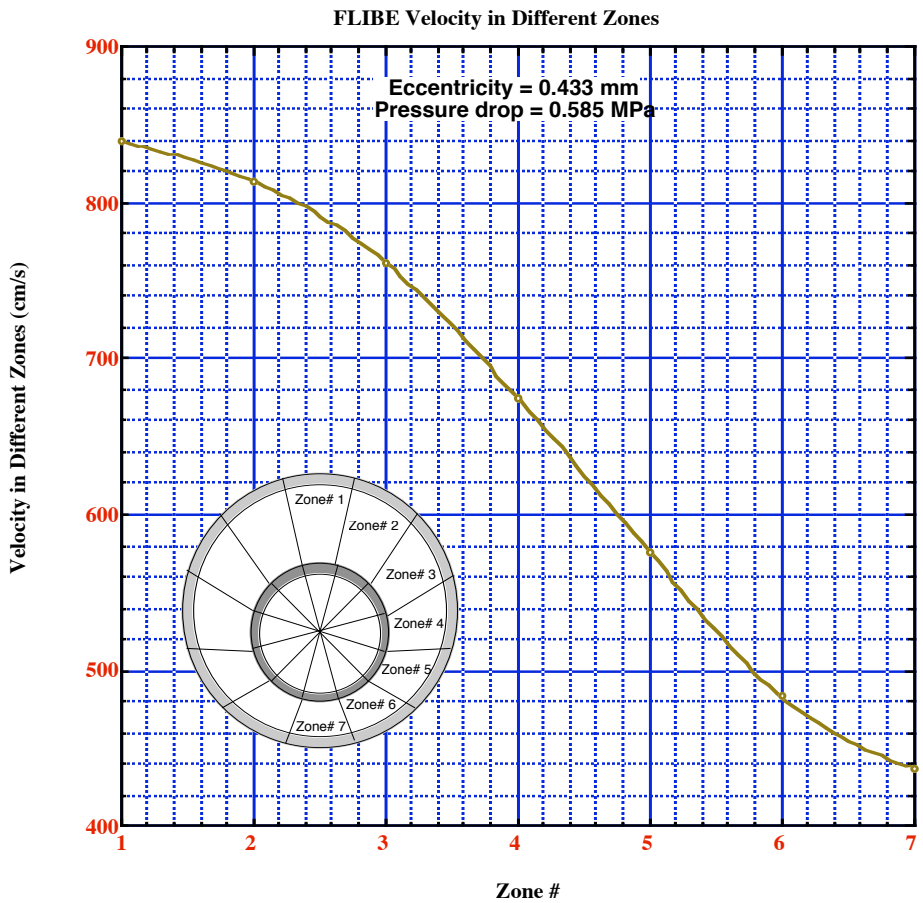
Impact of using eccentric lead tubes in the FW

- Results in larger cooling sub-channels at the front and smaller ones at the back
- For the same pressure drop, flow velocity will be larger with higher heat transfer coefficient at front where larger heat load needs to be removed
- The eccentric configuration was analyzed and compared to the concentric design with the same pressure drop for circular tubes

Eccentricity increases velocity at front zone with largest heat load



For concentric tubes:

Velocity is uniform = 7.21 m/s

Pressure drop = 0.585 MPa

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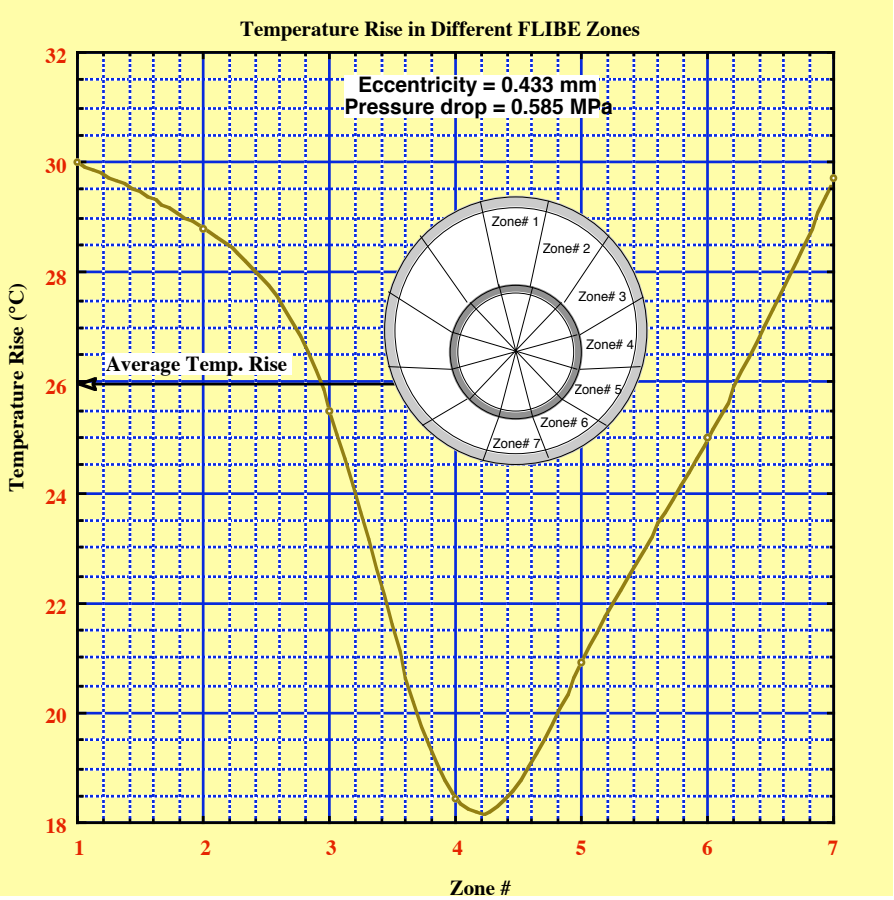
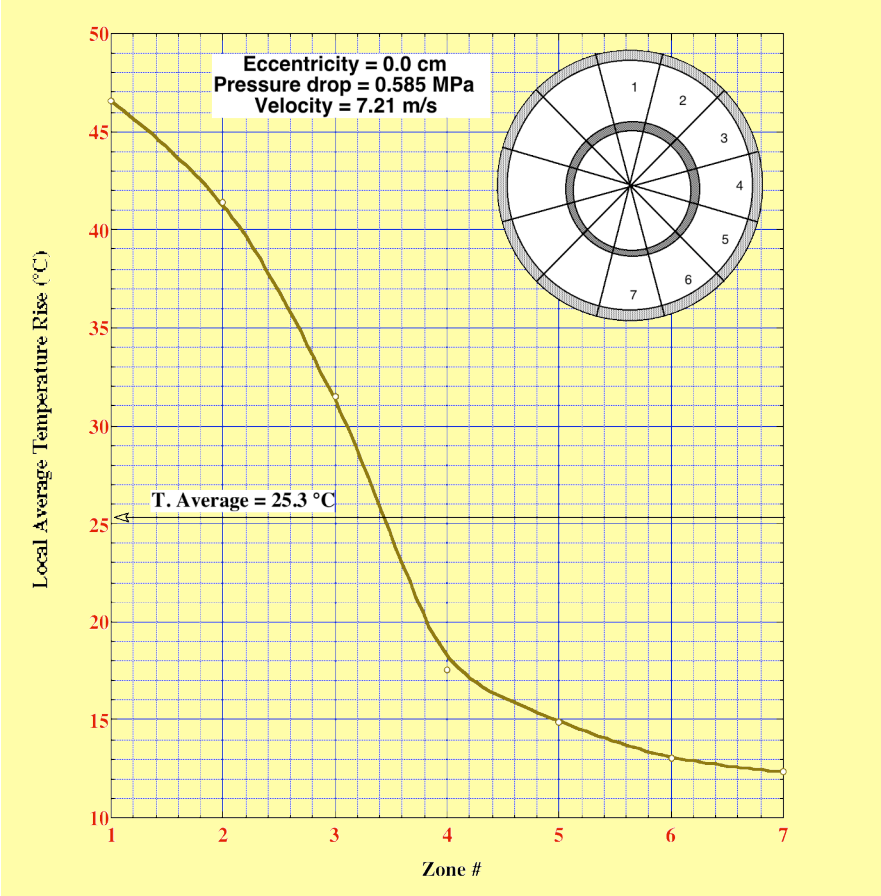
Eccentricity enhances Flibe temperature uniformity around the multiplier tube





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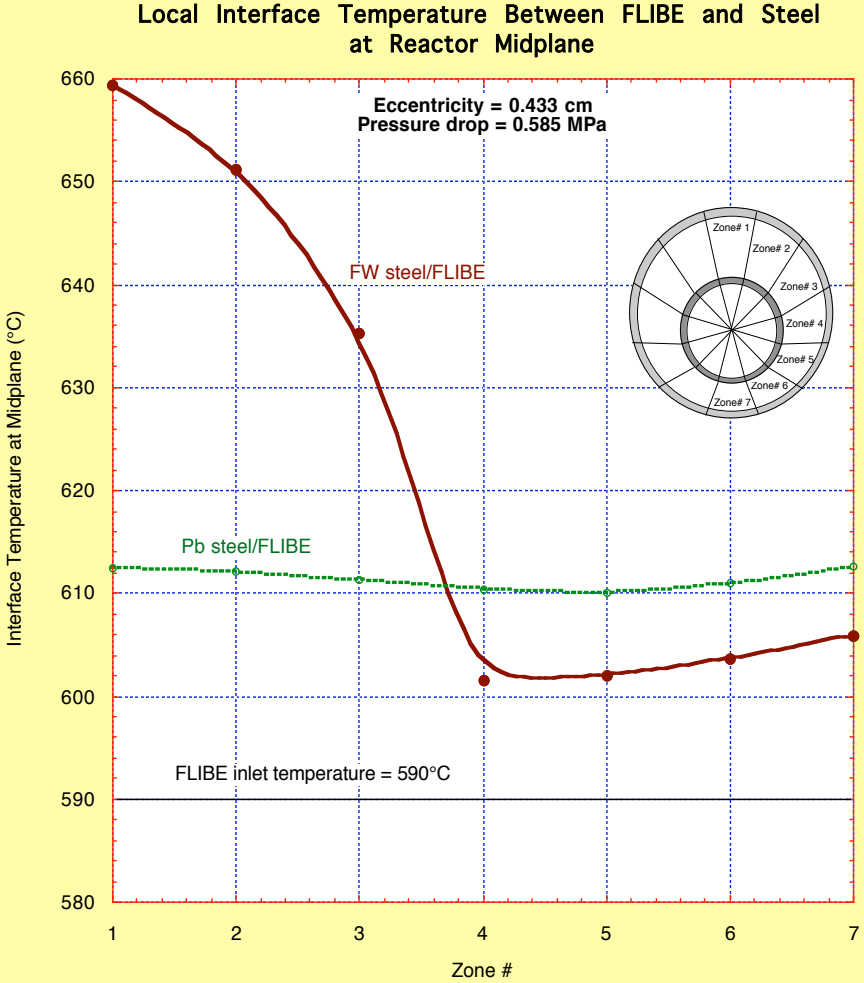
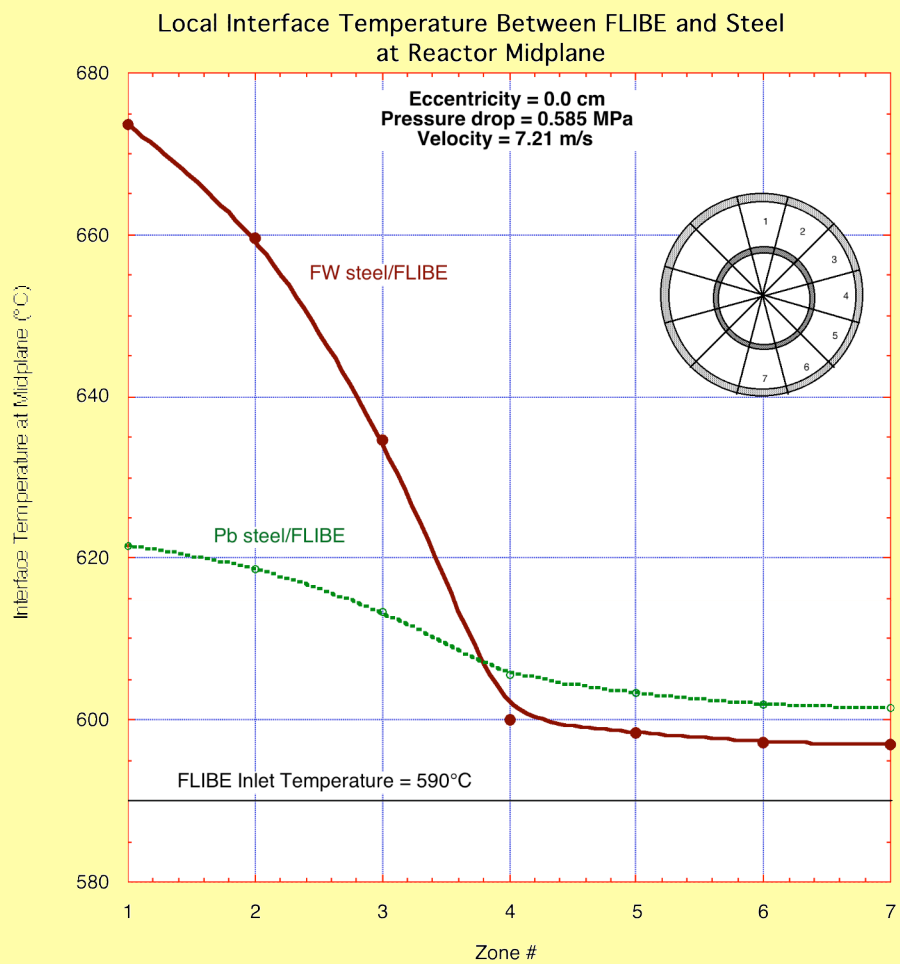
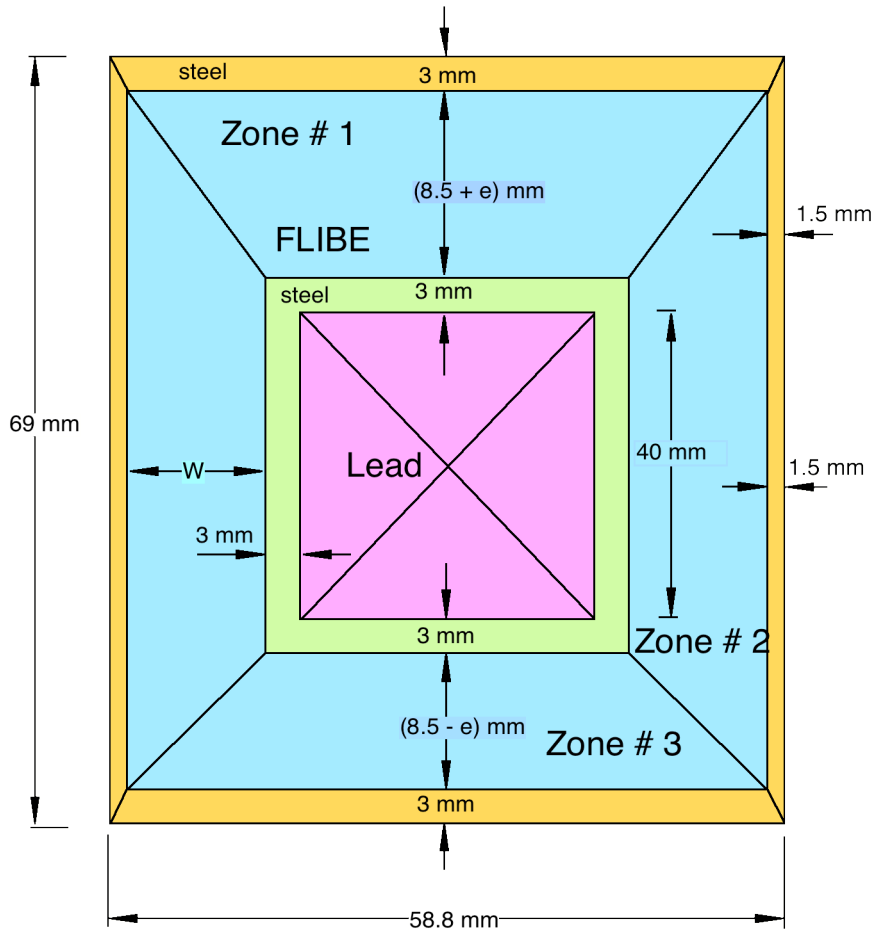
Eccentricity reduces the maximum interface temperature between FLIBE and steel





Analysis for rectangular FW tubes

- Design with circular FW tubes is easier to fabricate
- Mike Friend calculated stresses in a blanket element, taking into account coolant pressure in FW tubes as well as pressure in the large blanket central duct
- While stresses caused by pressure in FW tube itself are lower for the circular tubes, pressure in central duct leads to higher stresses in FW region compared to the rectangular reference design
- We optimized the reference rectangular design by using eccentric multiplier tubes and adjusting width of side Flibe channel
- MHD pressure drop was included using the results of Sergey's 2-D calculations
- Optimization performed for both OB and IB FW channels



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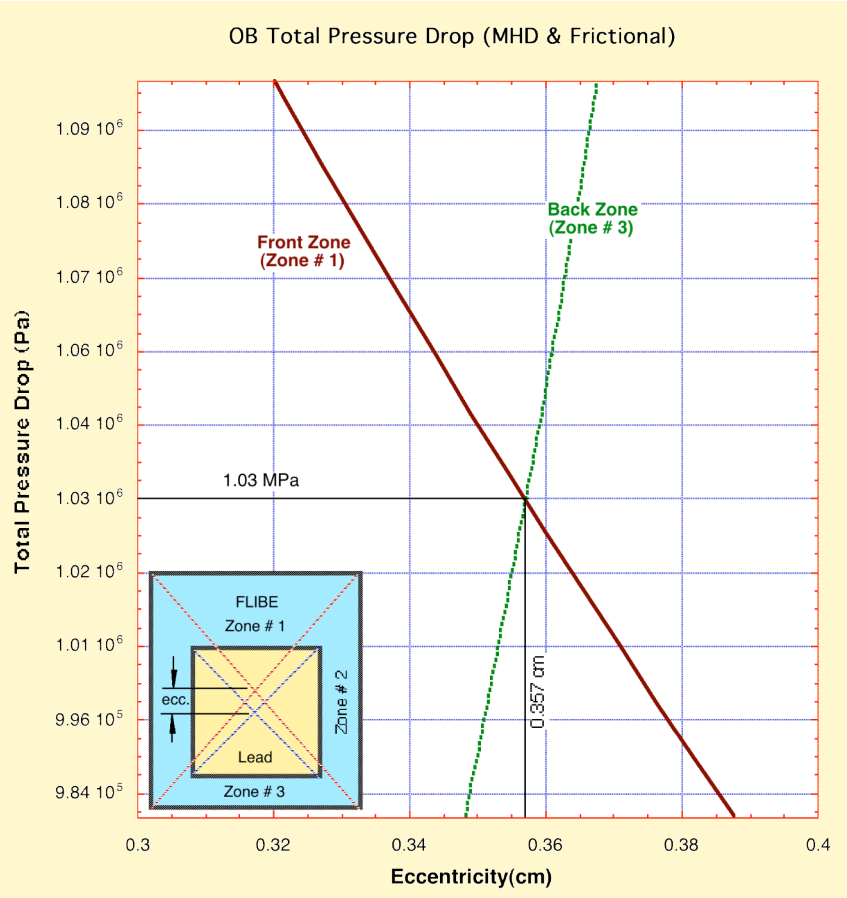
Optimized OB Rectangular FW tubes



- Size of the Flibe zones surrounding the Pb tube optimized to maintain uniform pressure drop and temperature rise
- Total pressure drop is 1.03 MPa
- Temperature rise is 30 °C

Zone #	Width (mm)	Velocity (m/s)	Temp. rise (°C)	Total Pressure Drop (MPa)	MHD Pressure Drop (MPa)
1	12.07	8.90	30	1.03	0.32
2	5	4.60	30	1.03	0.41
3	4.93	4.46	30	1.03	0.44

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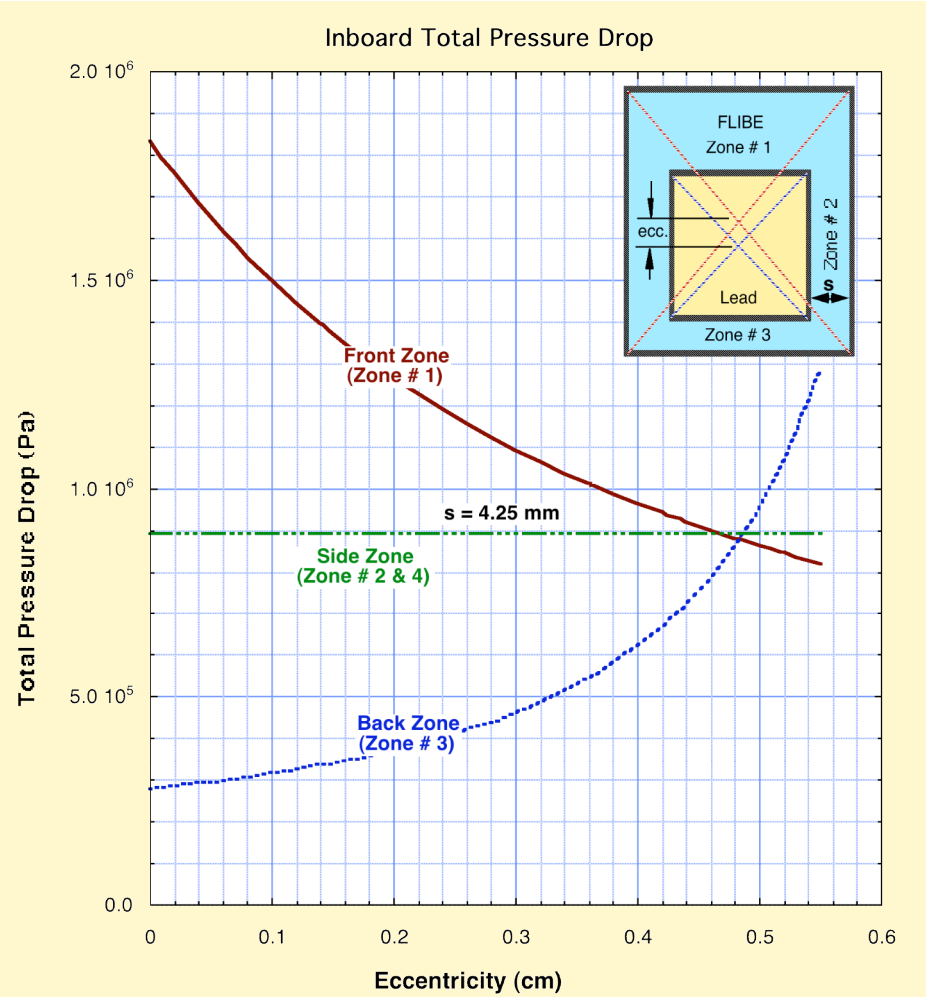
Interface Temperatures with Steel in OB Reference Rectangular FW Tubes

Zone #	Re	h ($W/m^2 K$)	Interface temp. between Flibe and outer steel (°C)	Interface temp. between Flibe and inner steel (°C)	Interface temp. between Pb and steel (°C)
1	39195	18003	667	630	680
2	8394	10858	611	637	660
3	8017	10566	611	633	662

- Volumetric flow rate per tube = 9043 cm^3/s
- Average Flibe velocity at midplane = 6.42 m/s
- Maximum interface temp. between FLIBE and FW steel = 667 °C
- Maximum interface temp. between lead and steel = 680 °C

Optimized IB Rectangular FW tubes



- Higher magnetic field (~8 T compared to ~4.3 T in OB)
- Lower heat load compared to OB
- Smaller velocity for the same temperature rise of 30 °C
- Total pressure drop is 0.88 MPa

Zone #	Width (mm)	Velocity (m/s)	Temp. rise (°C)	Total Pressure Drop (MPa)	MHD Pressure Drop (MPa)
1	13.33	6.11	30	0.88	0.55
2	4.25	3.13	30	0.88	0.51
3	3.67	3.38	30	0.88	0.35

Interface Temperatures with Steel in IB Reference Rectangular FW Tubes

Zone #	Re	h ($W/m^2 K$)	Interface temp. between Flibe and outer steel (°C)	Interface temp. between Flibe and inner steel (°C)	Interface temp. between Pb and steel (°C)
1	29703	12701	686	629	652
2	4860	7812	611	634	644
3	4530	8491	610	627	638

- Volumetric flow rate per tube = 6287 cm^3/s
- Average Flibe velovity at midplane = 4.69 m/s
- Maximum interface temp. between FLIBE and FW steel = 686 °C
- Maximum interface temp. between lead and steel = 652 °C

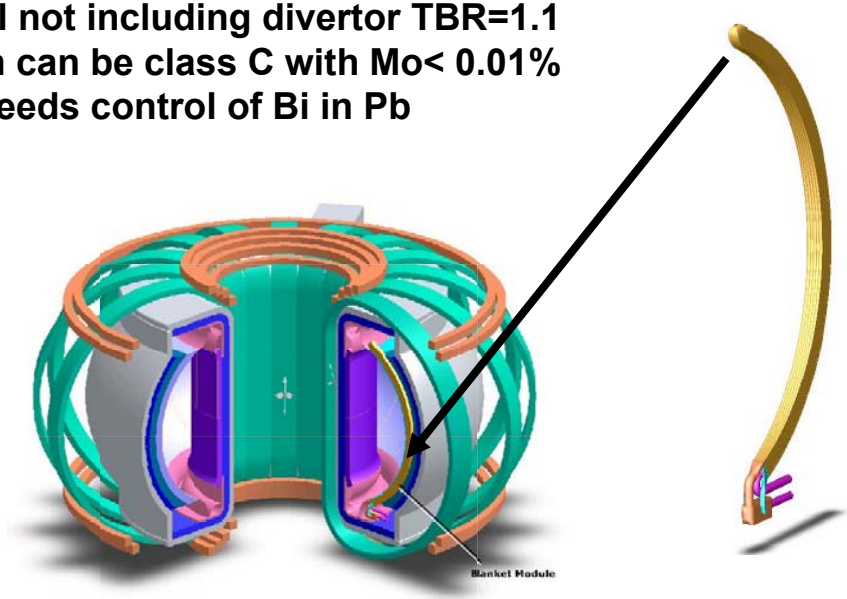
Conclusions

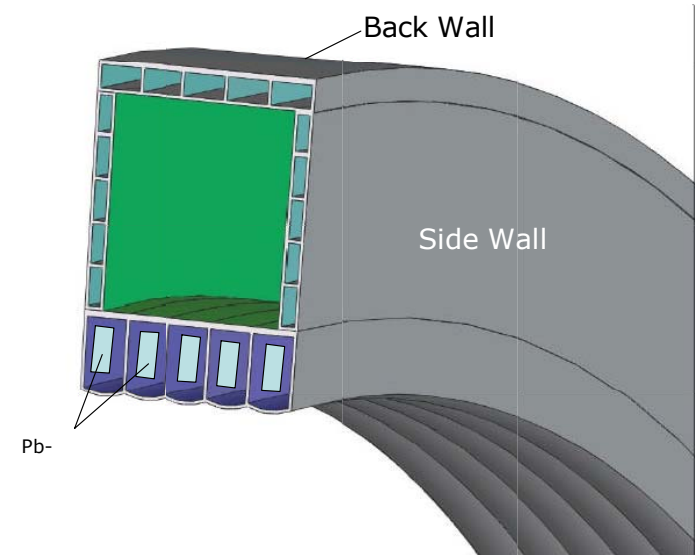
- Dimensions of FW Flibe channels optimized to maintain uniform pressure drop and temperature rise around the Pb tubes
- Total FW pressure drop is 1.03 MPa in OB and 0.88 MPa in IB, including MHD effects
- Volumetric flow rate per tube is 9043 cm^3/s in OB and 6287 cm^3/s in IB
- Maximum interface temperature between FLIBE and FW steel is 686 °C (in IB module)
- Maximum interface temperature between lead and steel is 680 °C (in OB module)

APEX-Task IV RE-CIRCULATING FLOW BLANKET DESIGN

A summary sheet (Materials: AFS/Flibe/Pb)

Temp. Limits: AFS<800° C, AFS/Flibe interfaces <700°C
Ave. Γ_n=3.8 MW/m^2, Max. φ_{fw}=1 MW/m^2
Flibe: Tin= 500° C, Tout=683° C, Flibe/He CCGT:η_{th}~48%
Overall not including divertor TBR=1.1
Design can be class C with Mo< 0.01%
Also needs control of Bi in Pb





FW/Blanket Cross-section

Key Issues:
AFS/Pb compatibility (Be is an alternative multiplier)
HF control
AFS design properties and components fabrication

Workshop Agenda

C. Wong, General Atomics, Jan. 2003