# Task III
# CLiFF Configuration Studies

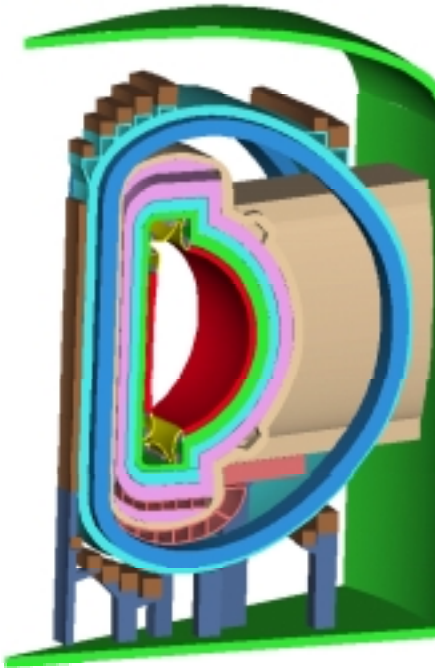
Presented by B. Nelson, P. Fogarty

Albuquerque Meeting
November 15-17, 2000

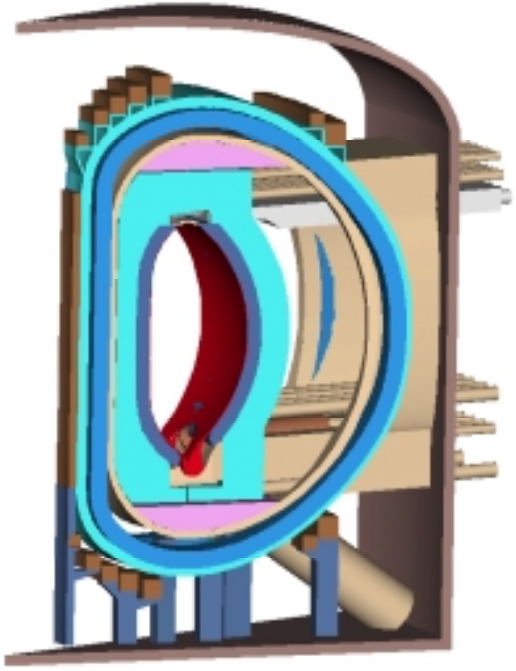
# Outline

- Review of design parameters and assumptions for CLIFF configuration studies
- Configuration developed for Flibe and implications for changing to liquid metal
  - Fast Flow Components, Nozzle Design
  - Blankets & Piping
  - Divertor & Penetrations
  - Maintenance Concept
- Trade-off between efficiency and availability
- Plans
- Summary

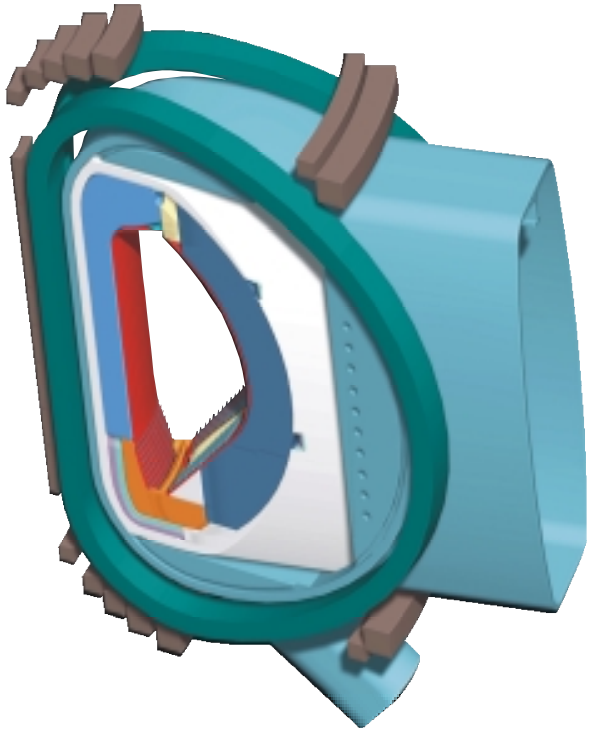
# ARIES RS used as basis for CLiFF



ARIES - RS Reactor Concept



Preliminary Modifications for CLiFF Concept



Final CLiFF Concept Configuration

# Parameters

| | ARIES* | APEX |
|---|---|---|
| Major Radius | 5.52 | same |
| Minor Radius | 1.38 | same |
| Plasma Aspect Ratio | 4 | same |
| Number of Sectors | 16 | same |
| Fusion power (MW) | 2171 | ~ 4000 |
| Neutron Power (MW) | 1736 | ~ 3400 |
| Alpha power (MW) | 433 | ~ 600 |
| Fusion power density (MW/m3) | 6.38 | ~ 12 |
| Average neutron load (MW/m2) | 4.03 | 7 |
| Peak neutron load (MW/m2) | 5.67 | 10 |
| Average FW surface heat flux (radiative), MW/m2 | 0.4 | 1.5 |
| Peak FW surface heat flux, MW/m2 | 0.47 | 2 |

* Ref http://aries.ucsd.edu/PUBLIC/ariesrs.html

# Design Requirements

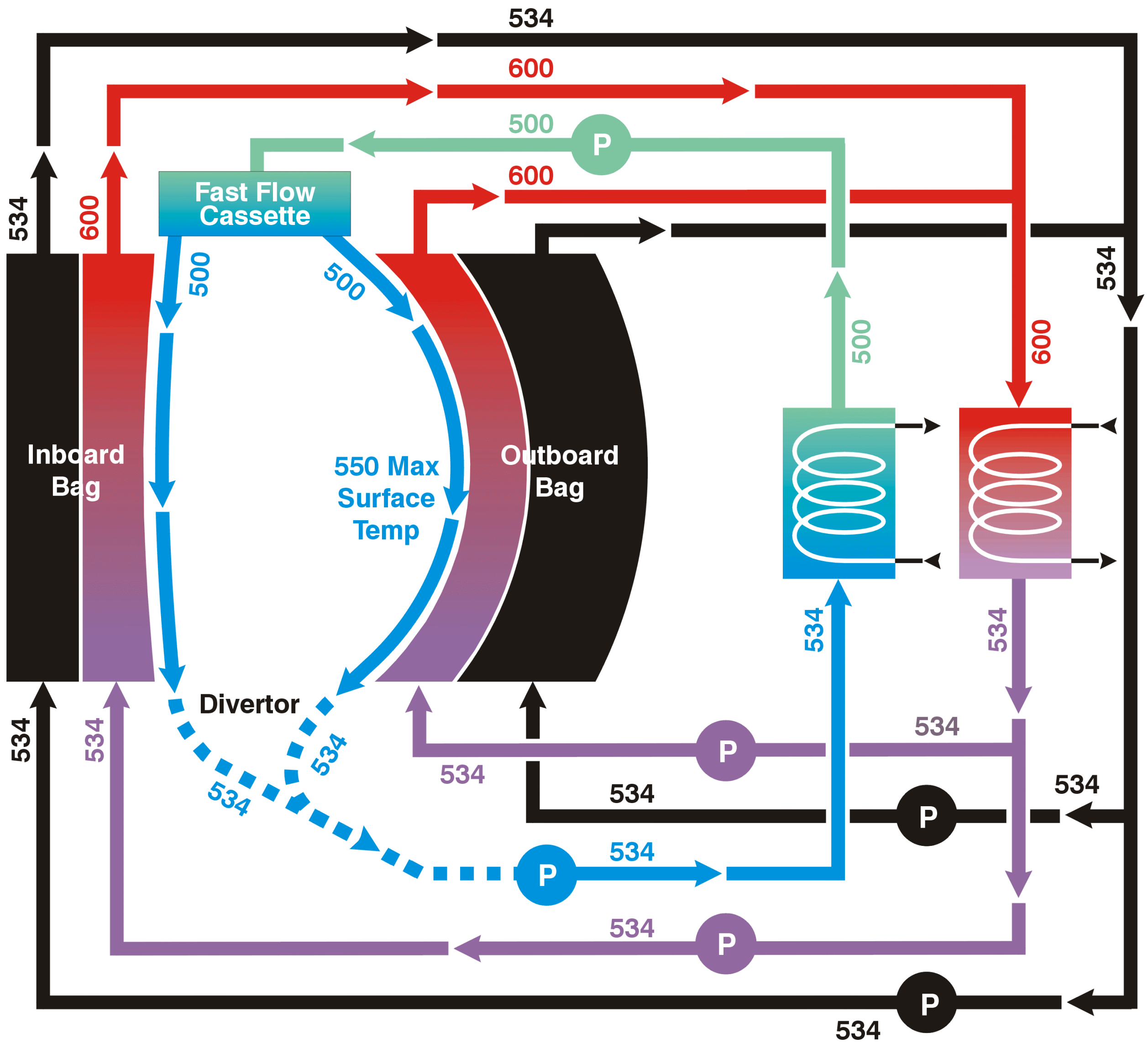
| Function | Requirement | Value/Goal |
|---|---|---|
| Power Extraction | Neutron Wall Load<br>Surface Heat Flux | 7 - 10 MW/m$^2$ avg*- peak*<br>2 MW/m$^2$* |
| Tritium Breeding | Self Sufficient | TBR > 1 |
| Shielding | Radiation exp. of coils (insulation)<br>Nuclear heating of coils (sc cable)<br>Re-weldable confinement boundary | < 1x10$^9$ Rad<br>< 1kW/m$^3$<br>< 1 appm He |
| Vacuum | Compatible with plasma<br>- Base partial pressure, non-fuel<br>- Base pressure, fuel (H,D,T) | <br>< 1x10$^{-9}$ Torr<br>< 1x10$^{-7}$ Torr |
| Plasma Exhaust | Divertor required | To remove helium |
| Penetrations | Plasma Heating Power Density<br>Diagnostics | ~6 MW/ m$^2$<br>View thru lab./mirrors |
| Operating Parameters | Pulse Length<br>Number of pulses<br>Disruptions | Steady State<br>< 3,000<br>TBD |
| Availability | Maximize total availability | $A_{Plant} > .75$<br>$A_{Blanket\ /\ FW} > .98$ |
| Safety | Confinement Boundaries | At least 2 |

* Values are minimum goals for steady state operation

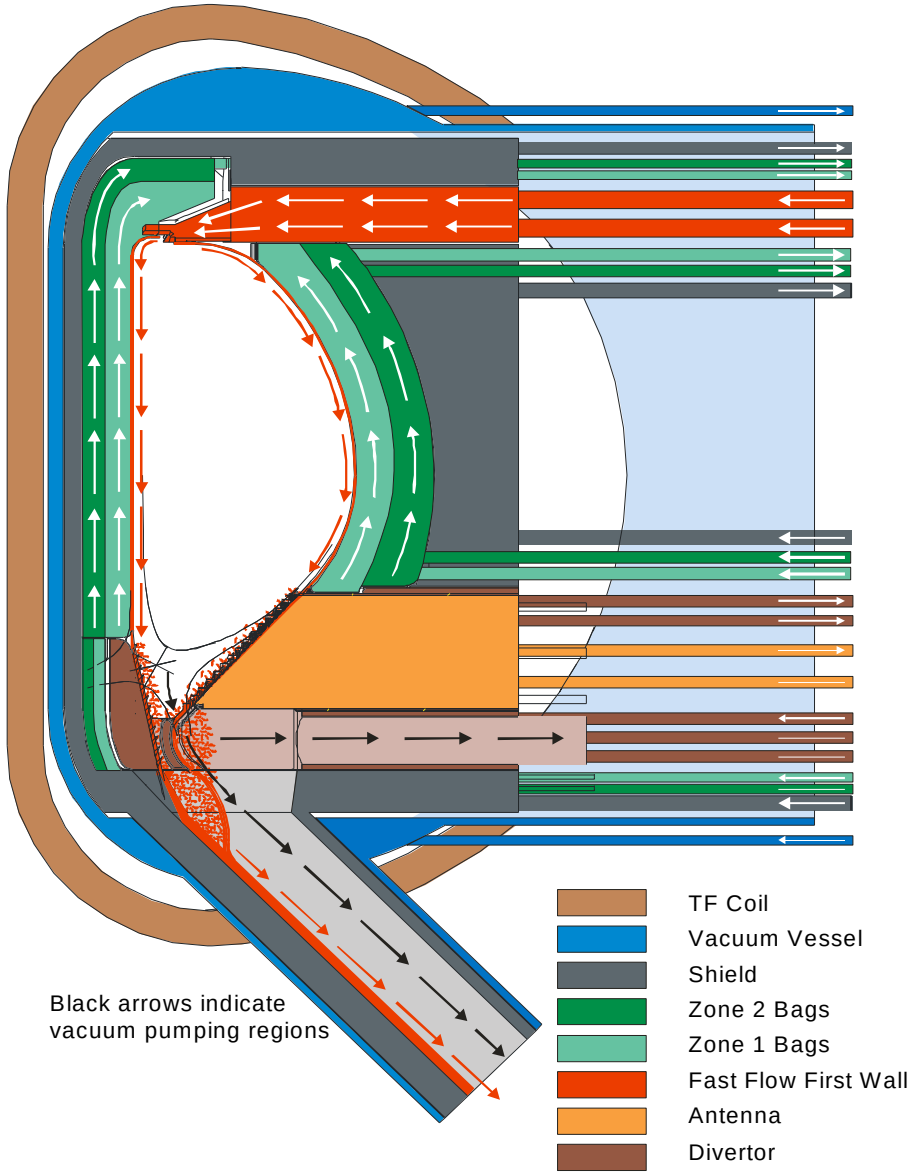
# Cliff concept

- Thin layer of fast flowing liquid intercepts surface heat flux
- Thick layer of slower flowing liquid in blanket intercepts neutron flux
- Cooler fast stream keeps vapor pressure low, while hotter coolant in blanket offers more efficient heat recovery
- CliFF concept has big payoff if it works, since
  - Small leaks *may* no longer be an issue
  - Damage / replacement of FW eliminated
- FY-00 study used Flibe for FW and blanket coolant, other coolant combinations to be investigated in FY-01

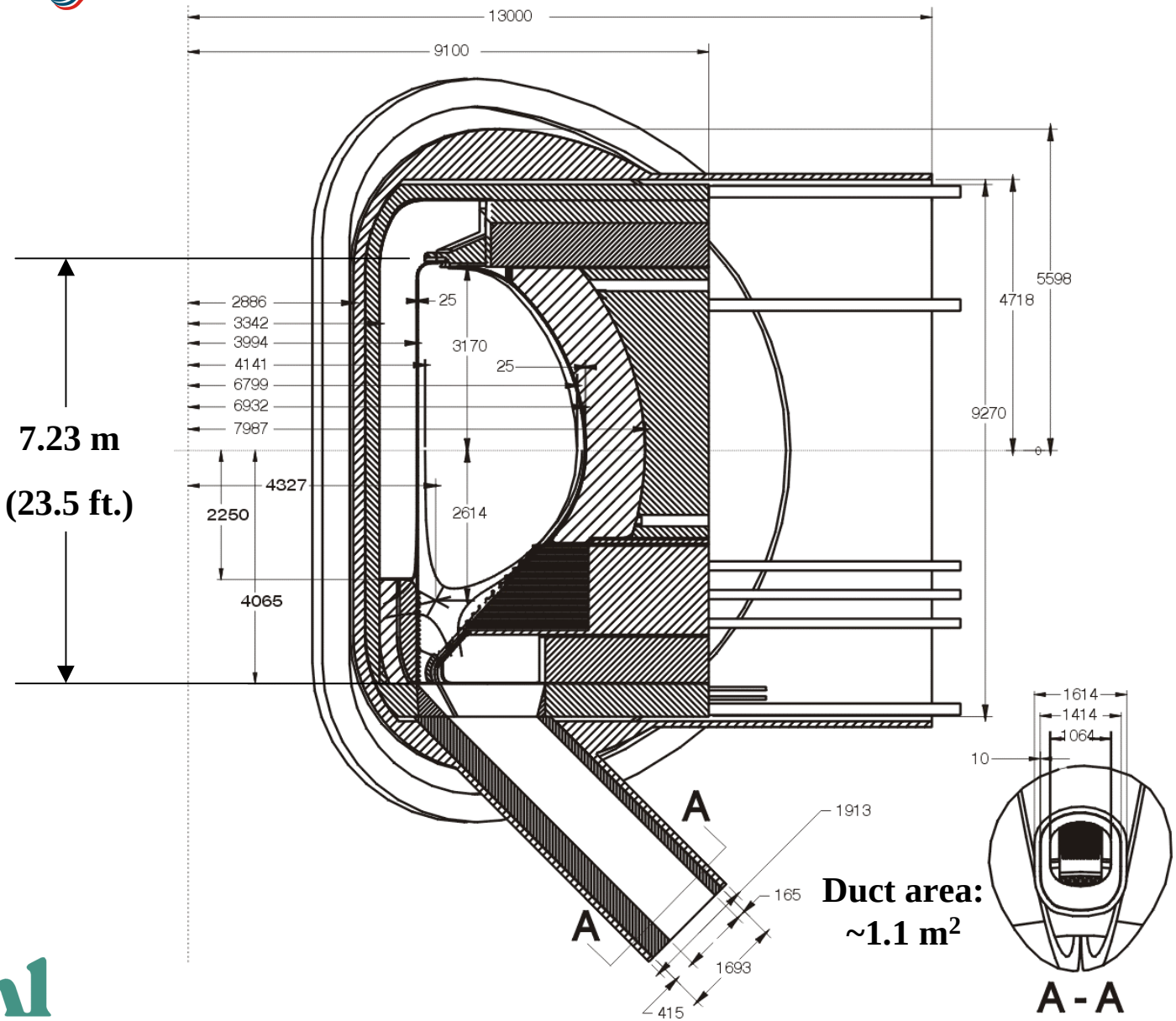
# Flow / Temperature Diagram - Flibe



# Flow / Vacuum Pumping Schematic

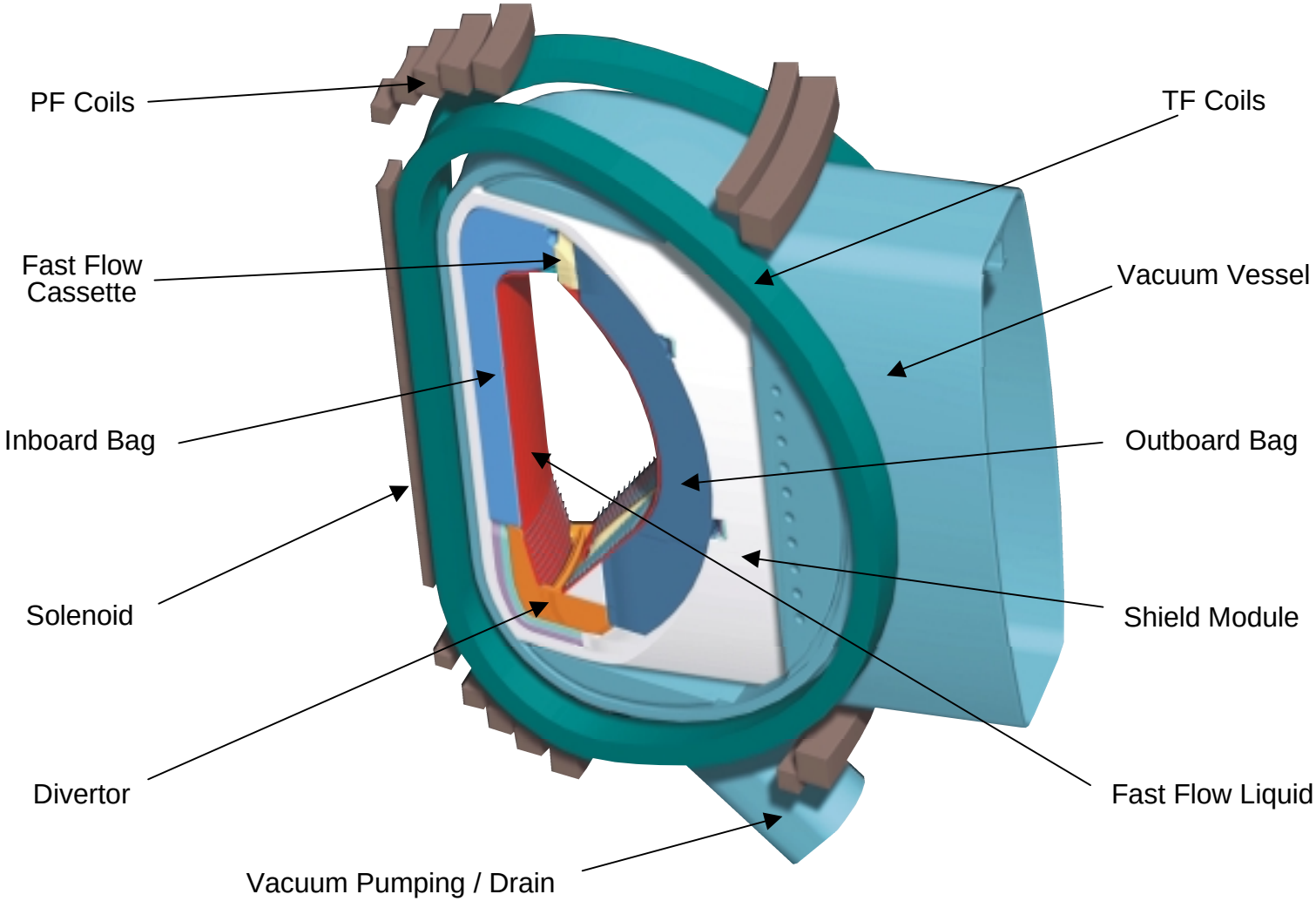


# CLiFF Design - Elevation View

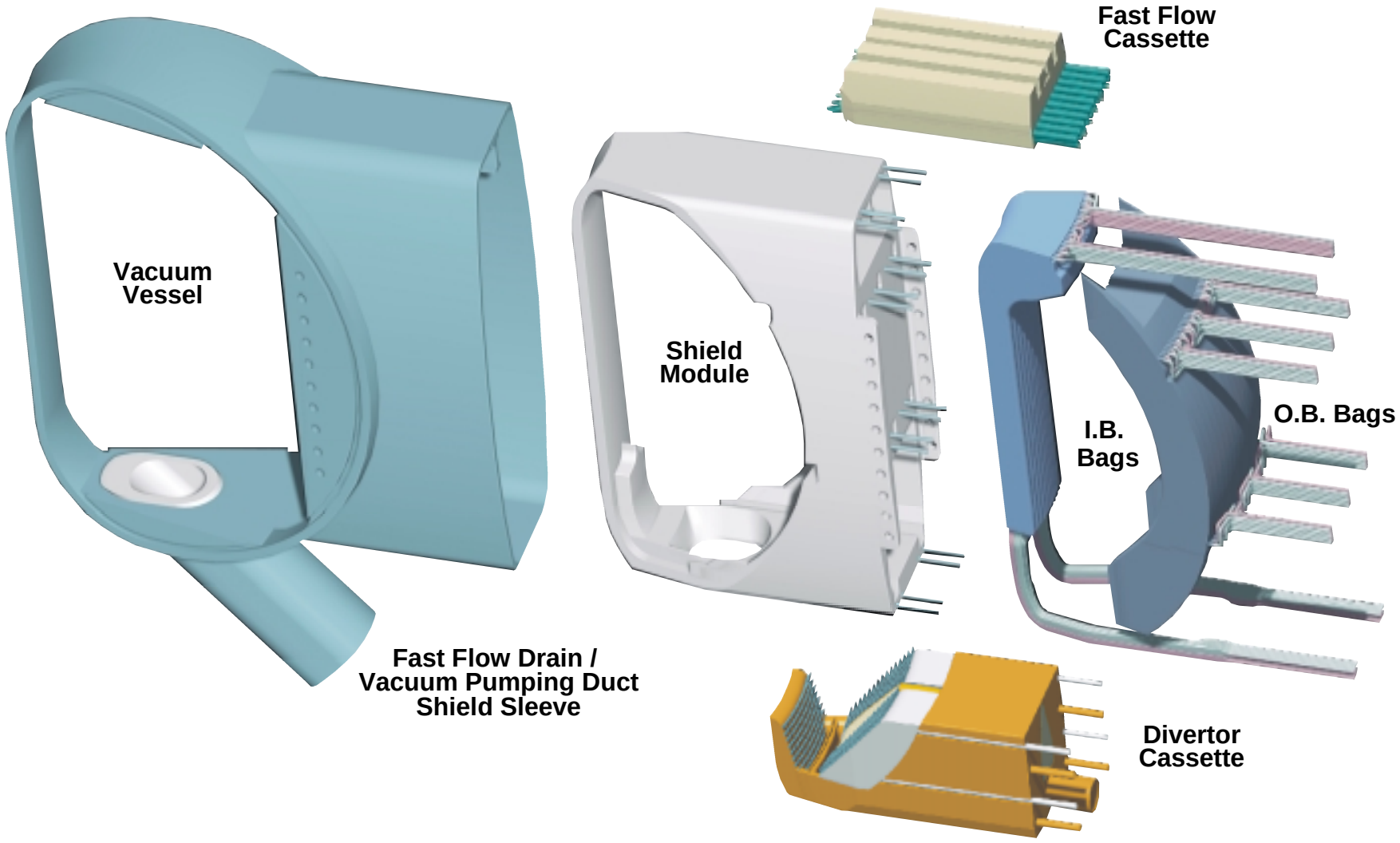



**Duct area: ~1.1 m$^2$**

# Device Configuration



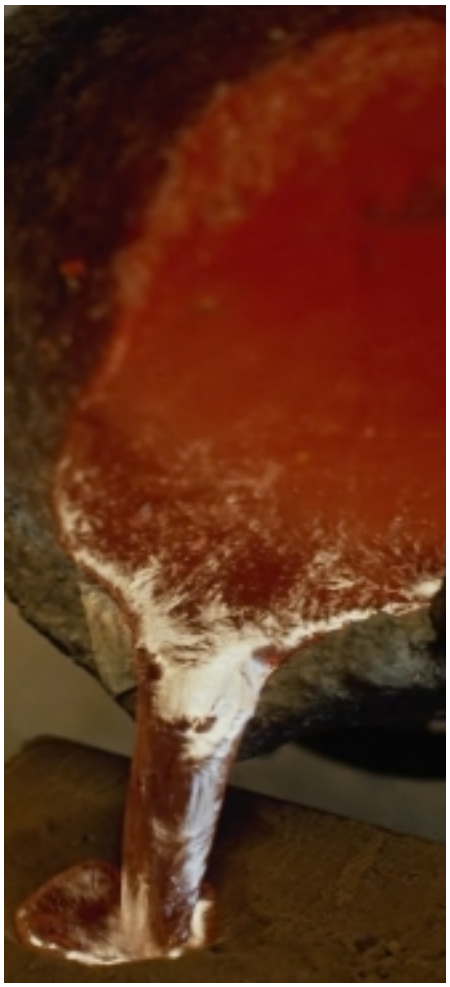
# Modular Components



# Component Properties

| Component Description | Volume ($m^3$) | Surface Area ($m^2$) | Density ($kg/m^3$) | Component Material | Sector Wt (kg) | Total Wt x 16 (kg) |
|---|---|---|---|---|---|---|
| Vacuum Vessel | 30. 2 | 361 | 8,027 | SST | 242,415 | 3,878,640 |
| Duct Sleeve | 5.41 | 46.9 | 8,027 | SST | 43,426 | 694,816 |
| Shield Module | 34.6 | 210 | 8,027 | SST | 277,734 | 4,443,744 |
| I.B. Bag (x 10) | 0.83 | 13.1 | 2,000 | Sic / Flibe / Be | 1,660 (16,600) | 265,600 |
| O.B. Bag (Ends x 2) | 1.04 | 14.3 | 2,000 | Sic / Flibe / Be | 2,080 (4,160) | 66,560 |
| O.B. Bag (Middle x 13) | .96 | 12.6 | 2,000 | Sic / Flibe / Be | 1,920 (24,960) | 66,560 |
| Bag Piping<br>I.B. – Upper<br>I.B. – Lower<br>O.B. – Upper<br>O.B. - Lower | <br>.083<br>.23<br>.07<br>.07 | <br>35.3<br>99.5<br>26.9<br>26.9 | <br>8,027<br>8,027<br>8,027<br>8,027 | <br>SST<br>SST<br>SST<br>SST | <br>666<br>1,850<br>562<br>562 | <br>10,656<br>29,600<br>8,992<br>8,992 |
| Film-Former | 9.25 | 16.3 | 8,027 | SST | 74,250 | 1,118,000 |
| Divertor | 19 | 208 | 8,027 | SST | 152,513 | 2,440,208 |
| I.B. & O.B. Fast Flows | 1.63 | 87.89 | 2,000 | Flibe | 3,260 | 52,160 |
| TOTALS | | | | | (842,958) 830 Tons | 13,417,326) 13,206 Tons |

# Flibe vs. Li or Sn Design



## Flibe Design

- Fast flowing film on surface
- Slower moving coolant in blanket "bags"
- Divertor / penetration cassette
- Full-sector maintenance

## Li or Sn Design

- No basic changes
- Details will be different

# Fast Flow on First Wall

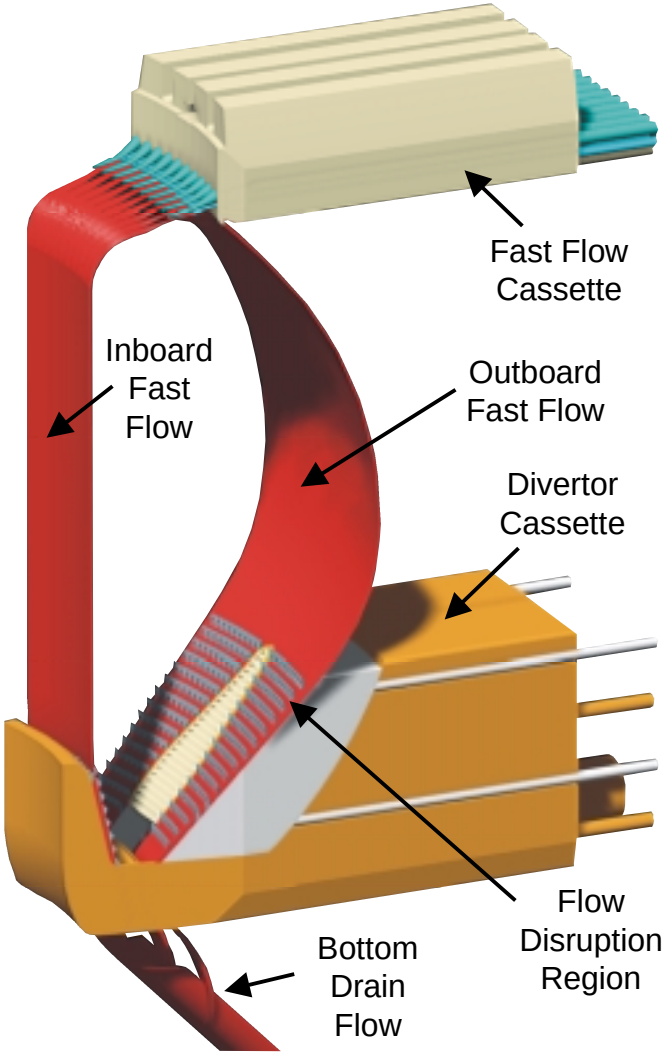
## Basic Design

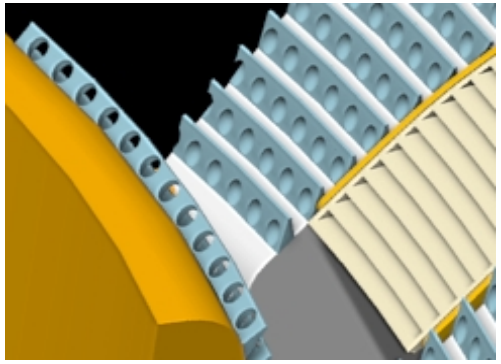
- Fluid introduced from cassette
- Nozzles arranged for mutual protection

## Li, Sn Design

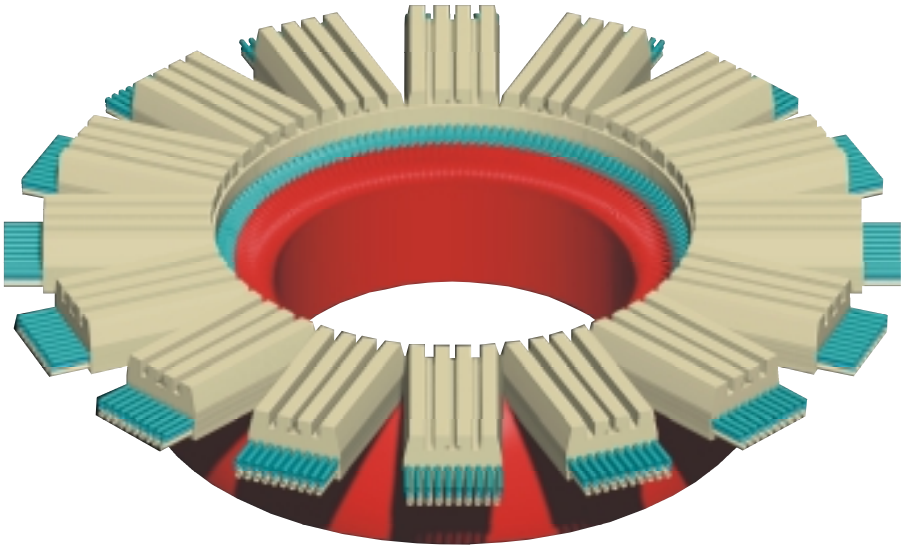
- MHD effects must be considered
- Nozzle / piping materials more limited
- Insulators probably needed
- Different temperatures, volumetric flow

# Fast Flow Components



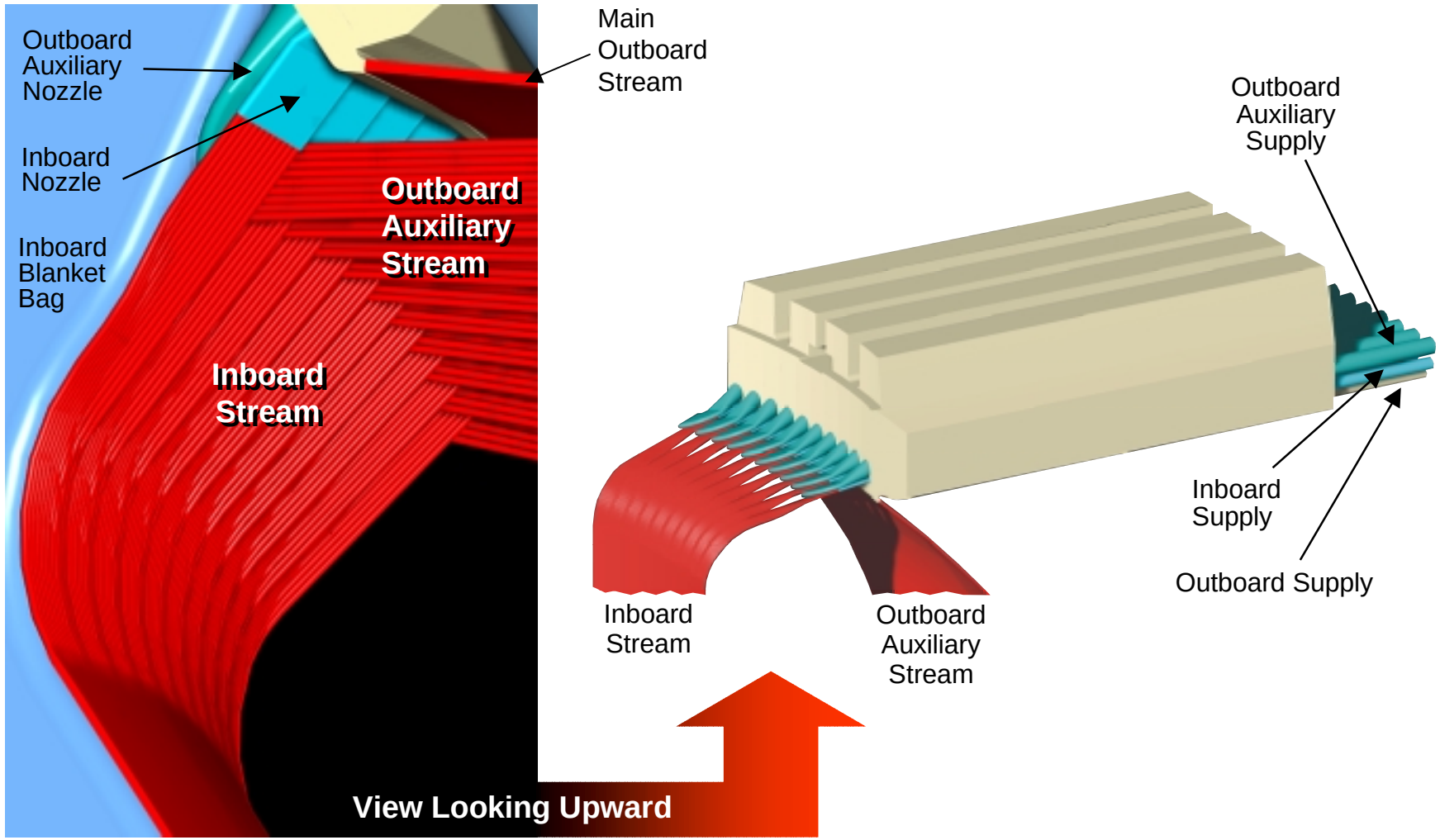



Close-up of Flow Disruption Baffles



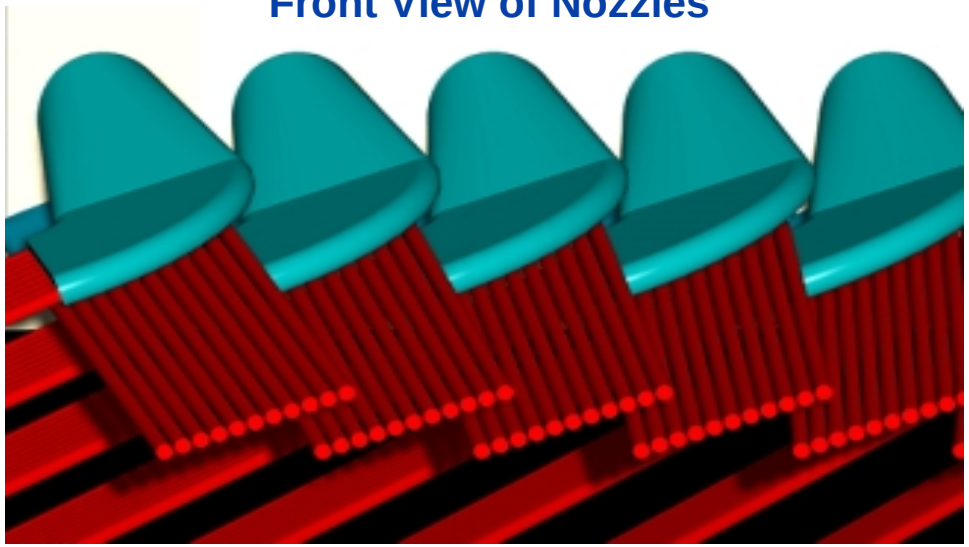
Top View Assembly Cut at Mid-plane

# Fast Flow Cassette

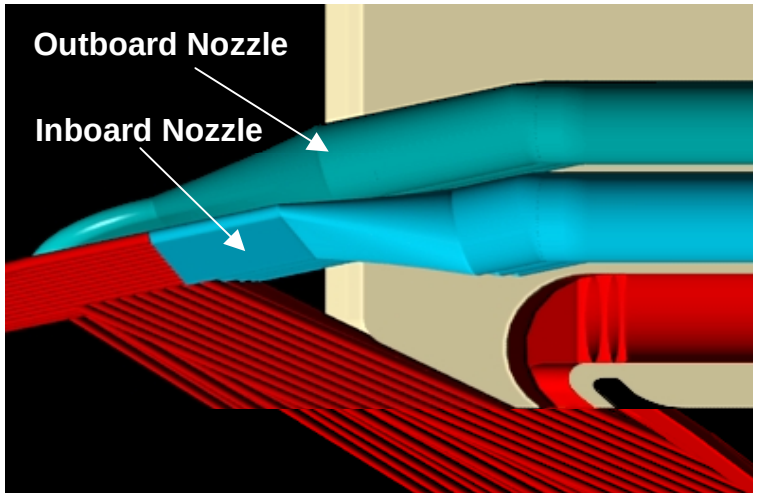


# Nozzle Design Configuration

## Front View of Nozzles

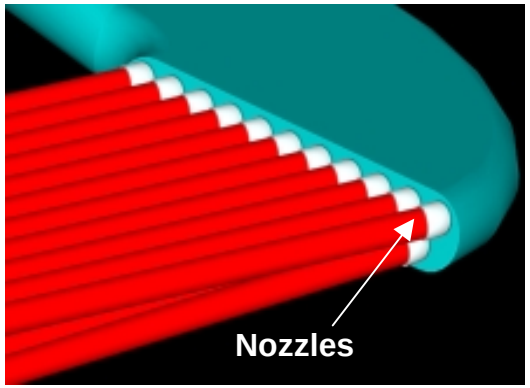


## Side View Cutaway of Nozzles




## View Looking Upward from a Mid-plane Cut

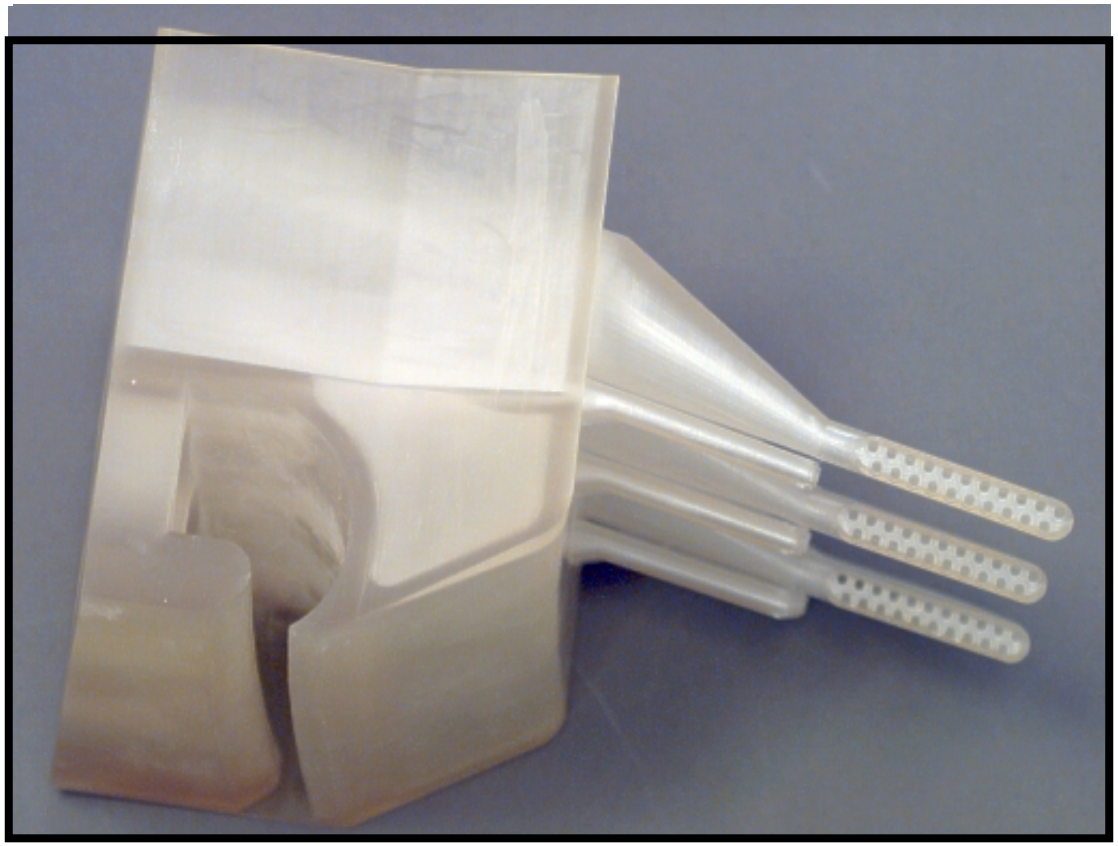
## Adjustable Nozzles

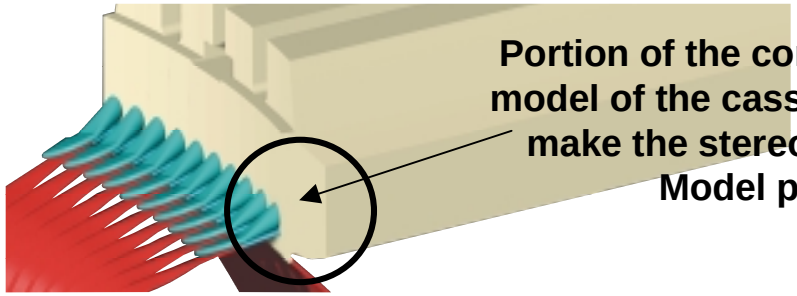



ornl

UT-BATTELLE

# Stereolithography Model





**Portion of the computer CAD model of the cassette used to make the stereolithography Model pictured here**

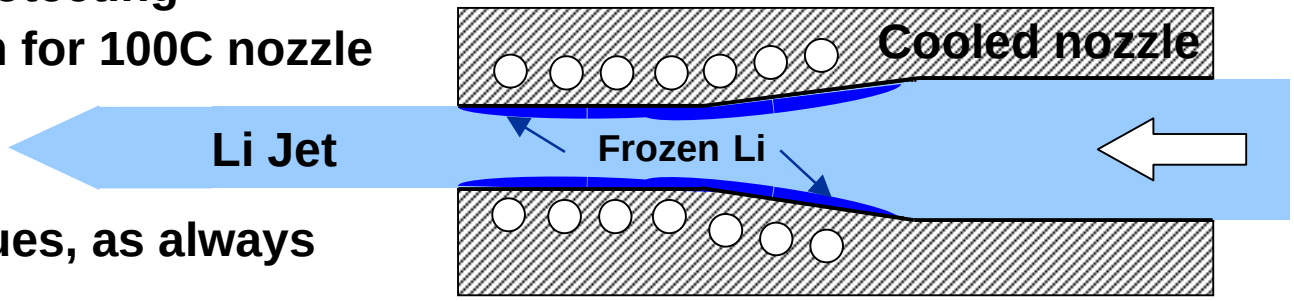
# Scheme to reduce nozzle wear

## We want to reduce velocity and temperature at Li-nozzle interface

- Nozzle erosion proportional to square of velocity (or worse)
- Reaction of lithium with coatings, structural materials decreases with temperature

## Can we freeze a thin layer of lithium inside the nozzle?

- Nozzle is self-protecting
- Layers of ~ 1mm for 100C nozzle
- Many, many issues, as always



# FW / Nozzle Design Issues for Li, Sn

- Geometry of first wall flow should be parallel to flux surfaces to reduce radial field components, but this is not really possible
- Calculations of MHD effects must include 3-D components of velocity and magnetic field , free streams have advantage
- Lack of compatible insulator coating, erosion and degradation of nozzles may force frequent replacement
- Nozzles not well shielded from neutron fluence, may affect insulating coatings further
- Image currents in FW liquid due to plasma motion may have undesirable effects on flow

# Blankets and Piping

## Flibe Design

- SiC “bag” blankets intercept most heat, operate at high temperature, protect VV, require Be layer for breeding
- Piping routed to minimize flow velocity, maximize shielding

## Li Design

- SiC not compatible with high temp Li,
- MHD a problem, but conducting wall may eliminate need for additional passive stabilizer
- Lithium less effective as shield

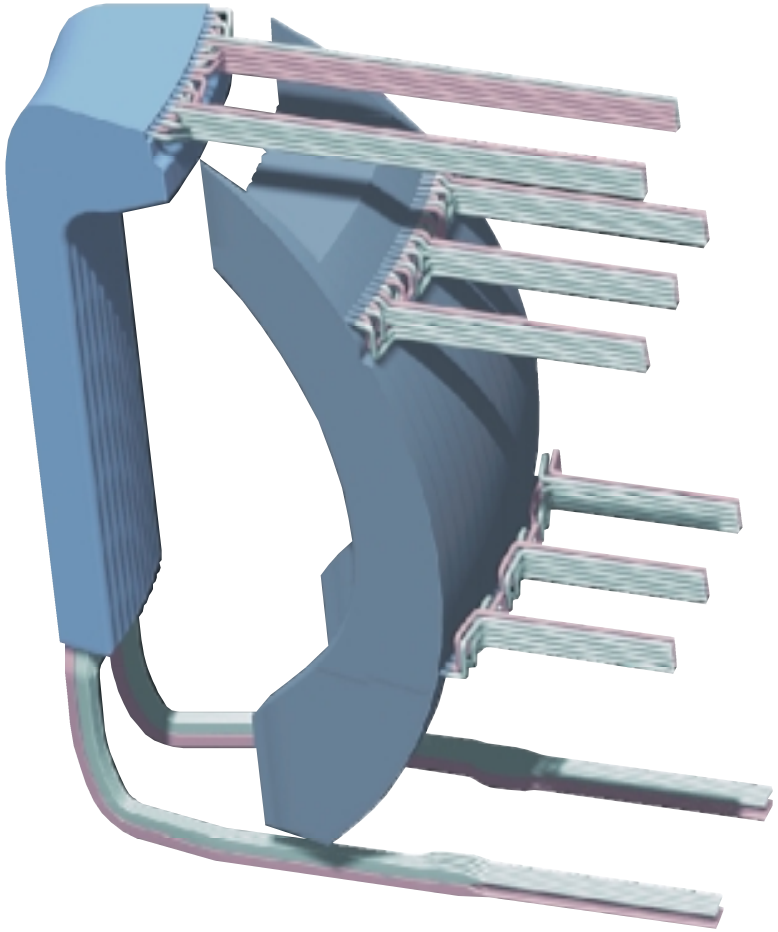
## Pb-Li Design

- Better shield, better breeding (no Be), better mat’l compatibility at high temperature
- melts at lower temperature (leaks won’t seal)

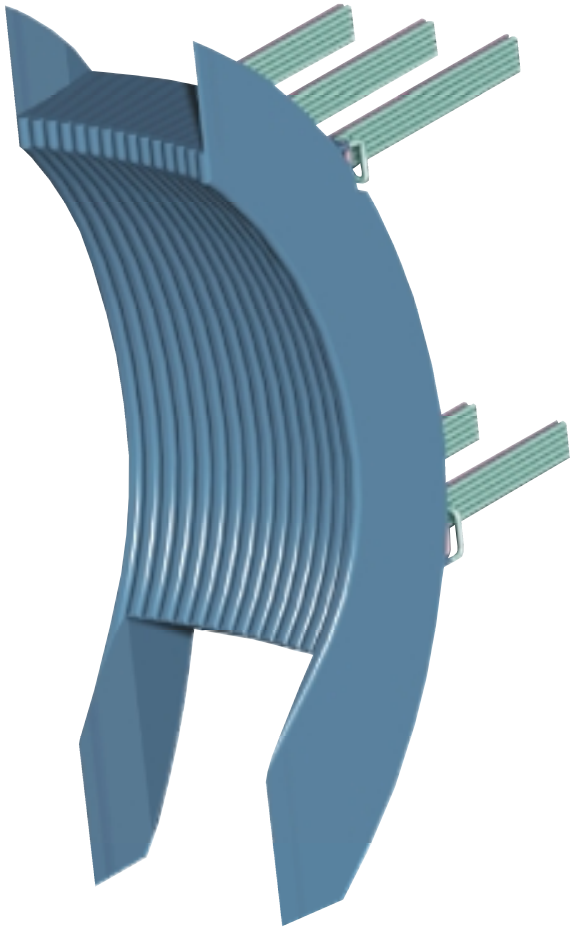
# Piping Specifications for Flibe

| Circuit type | Power to circuits in one sector (MW) | Tinlet (C) | Toutlet (C) | Flow rate per sector (l/s) | No of circuits per sector | Pipe size (I.D.) (inches) | Velocity (m/s) |
|---|---|---|---|---|---|---|---|
| **First wall fast flow** | | | | | | | |
| IB (inboard) | 26.9 | 475 | 500 | 258 | 10 | 6.0 | 1.4 |
| OB (outboard) main flow | 33.3 | 475 | 500 | 327 | 10 | 6.0 | 1.8 |
| OB (outboard) auxiliary | 25.0 | 475 | 500 | 242 | 10 | 5.5 | 1.6 |
| Flow under OB penetration | 3.0 | 475 | 500 | 29 | 21 | 1.4 | 1.4 |
| **"Bag" blankets** | | | | | | | |
| IB, plasma side | 13.6 | 500 | 600 | 28 | 10 | 2.3 | 1.0 |
| IB, coil side | 20.1 | 500 | 600 | 41 | 10 | 2.3 | 1.5 |
| OB, plasma side | 26.9 | 500 | 600 | 55 | 15 | 2.3 | 1.4 |
| OB, coil side | 45.4 | 500 | 600 | 93 | 15 | 2.3 | 2.3 |
| IB, divertor, plasma side | 3.4 | 500 | 600 | 7 | 2 | 2.0 | 1.7 |
| IB divertor, coil side | 1.8 | 500 | 600 | 4 | 2 | 1.5 | 1.6 |
| OB divertor, plasma side | 9.7 | 500 | 600 | 20 | 2 | 3.5 | 1.6 |
| OB divertor, coil side | 15.3 | 500 | 600 | 31 | 2 | 4.0 | 1.9 |
| **Divertor sled** | | | | | | | |
| IB structure | 2.8 | 500 | 520 | 28 | 1 | 6.0 | 1.5 |
| OB structure | 0.1 | 500 | 520 | 1 | 1 | 2.0 | 0.4 |
| **Film former cassette body** | 10.2 | 500 | 520 | 105 | 1 | 8.0 | 3.2 |
| **Penetration** | 16.3 | 500 | 550 | 67 | 1 | 8.0 | 2.1 |
| **Main shield** | | | | | | | |
| IB shield | 0.3 | 500 | 510 | 7 | 1 | 3.0 | 1.4 |
| OB shield | 0.1 | 500 | 510 | 2 | 1 | 2.0 | 1.0 |
| **Vacuum vessel** | | | | | | | |
| IB Vessel | 0.1 | 500 | 505 | 4 | 1 | 3.0 | 0.8 |
| OB Vessel | 0.0 | 500 | 505 | 1 | 1 | 2.0 | 0.3 |
| **TOTAL ALL SECTORS** | 4069 | | | 21601 | | | |

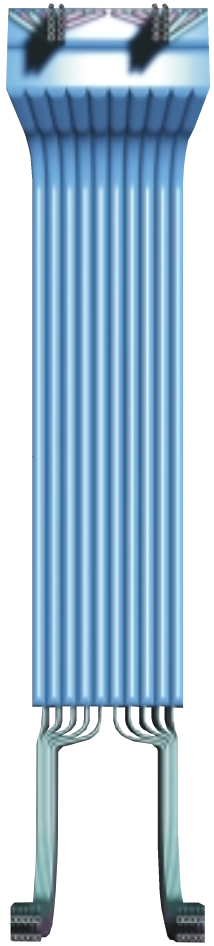
# Blanket "Bag" Design



Sector Blanket Assembly



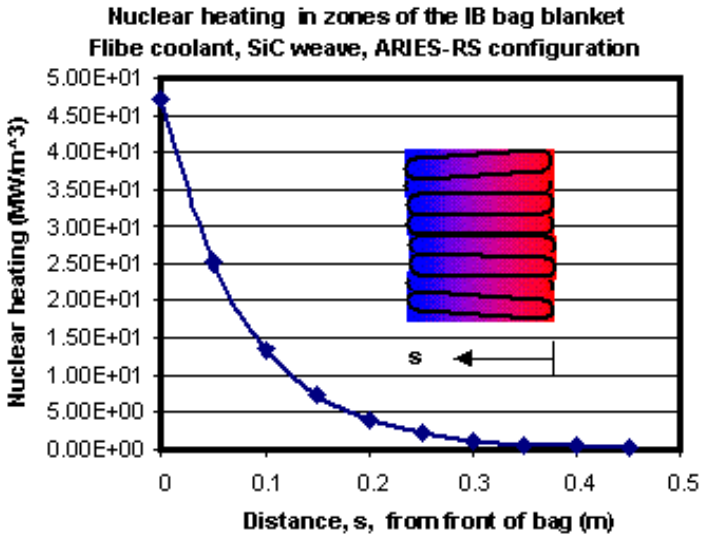
Outboard Assembly



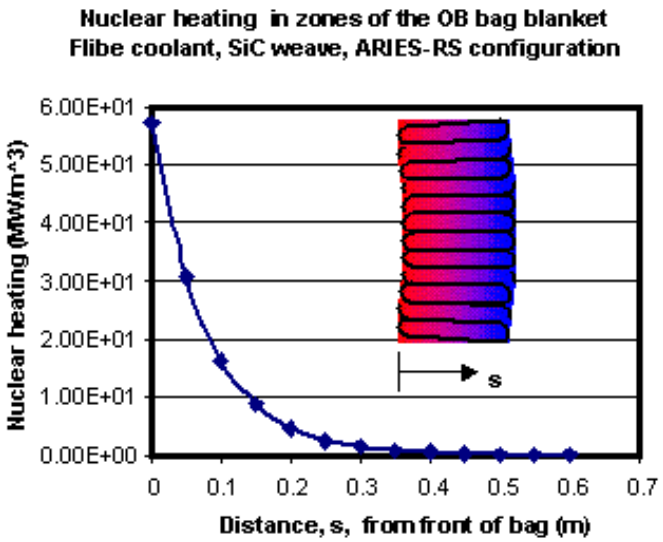
Inboard Assembly

# Nuclear Heating & Integrated Power

**Inboard**

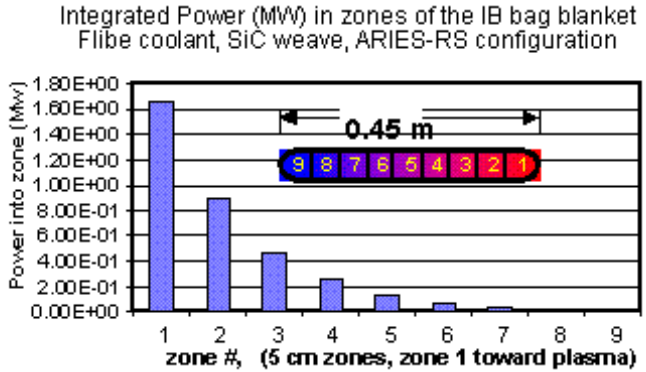



**Outboard**

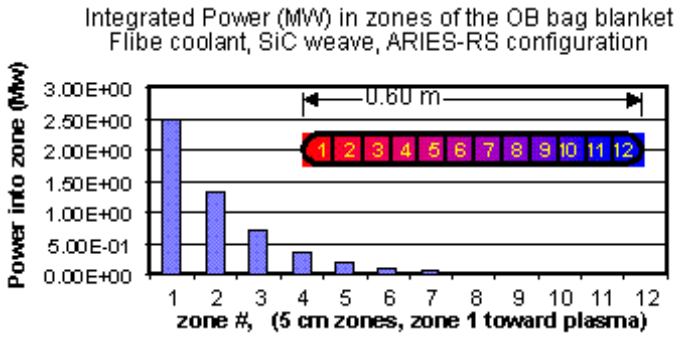



**Most of the power is deposited in the first 10 cm of blanket**

**Inboard**



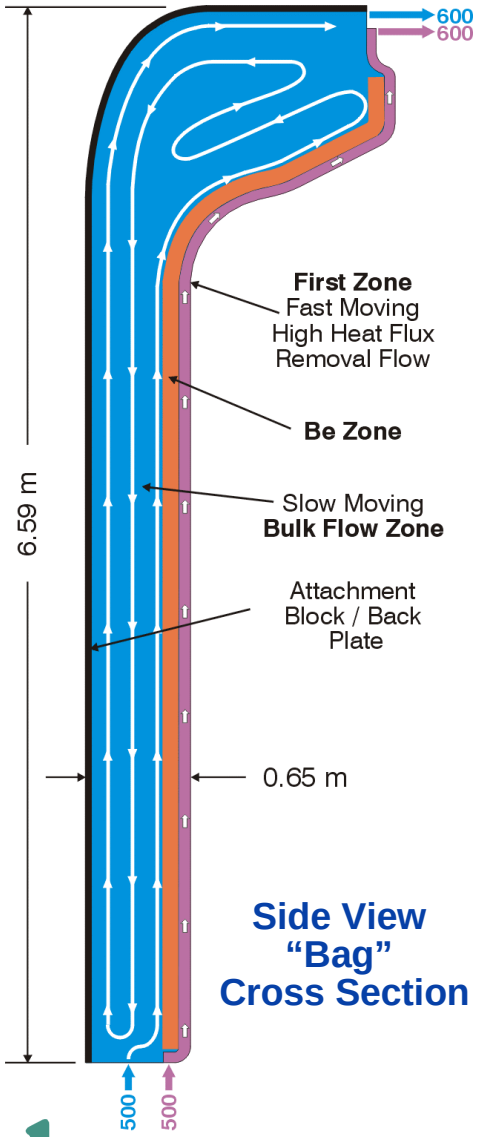

**Outboard**



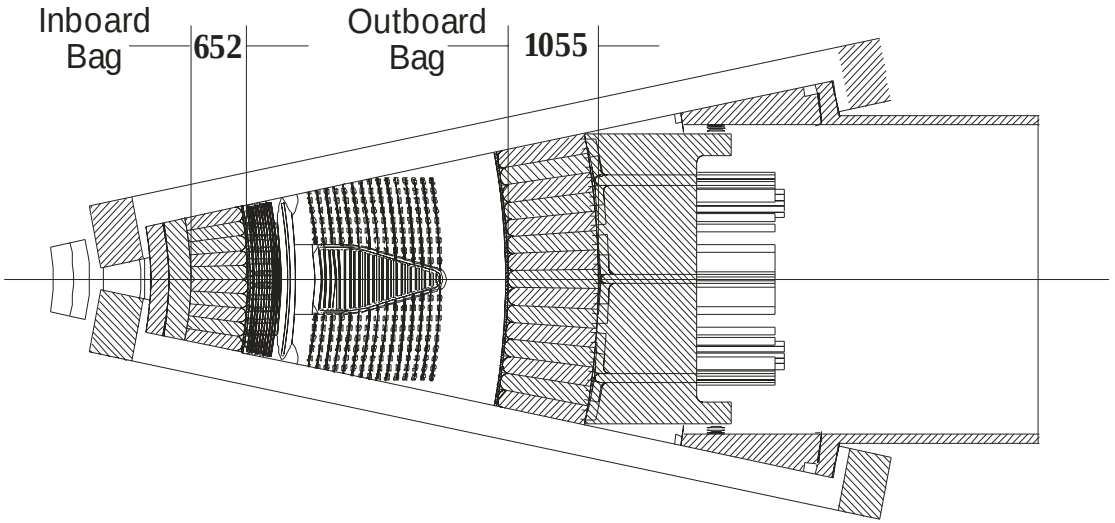

ornl

UT-BATTELLE

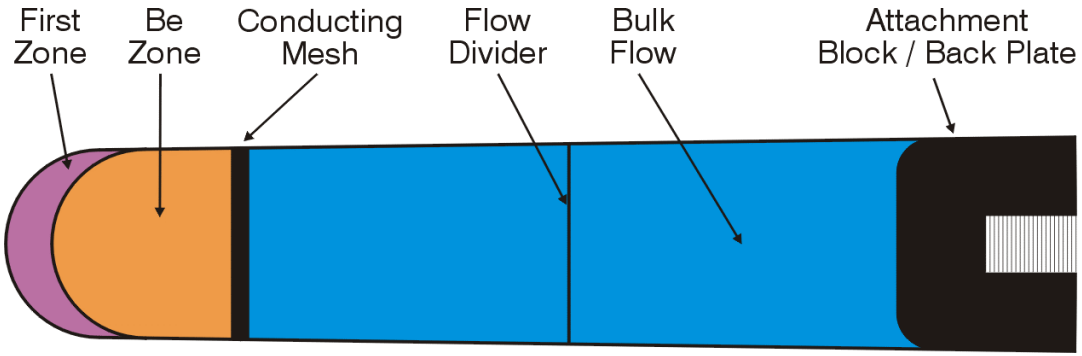
# Blanket Configuration, Flibe




**Side View "Bag" Cross Section**

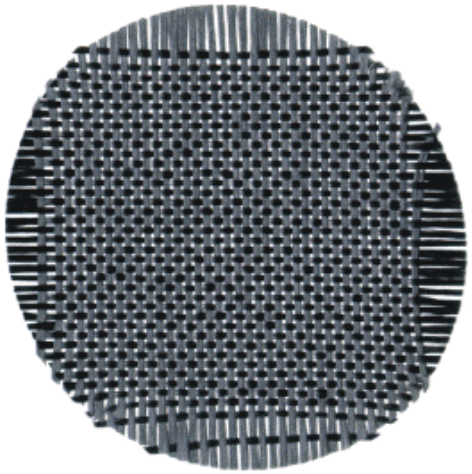



**Mid-plane Machine Cross Section**




**Top View "Bag" Cross Section**

# Woven Mesh "Bag" Advantages



Standard Weave in
Hi Nicalon Material

Satin Weave in
Tyranno Material

Material has
flexibility for
shaping bags

- Bag is woven from SiC fibers
- Structure remains flexible, even though material is very brittle
- No, or very minimal thermal stress
- SiC fabric is commercially available
- Small bag leaks should not be a fatal problem
- Vapor pressure is suppressed by cooler flow over surface

# Alternate Design Option

## Alternate design uses Li, Sn, or other liquid on surface, retains Flibe for coolant in blanket and structure

- Better shielding than Li, but not better than Pb-Li
- Fewer MHD problems
- More material choices if Li or Sn at low temp
- Seepage, leaks from blanket are “sealed” by lower temperature lithium flow
- Still requires Be for breeding
- May require separate passive stabilizing structure

# Divertor and Penetrations

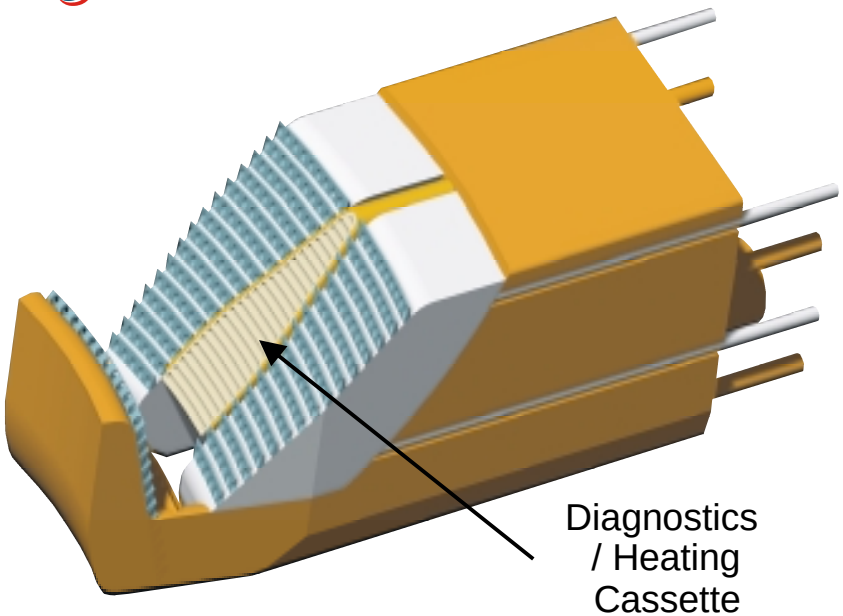
## Flibe Design

- Single cassette for divertor and penetration
- Large pumping / exit duct under penetration

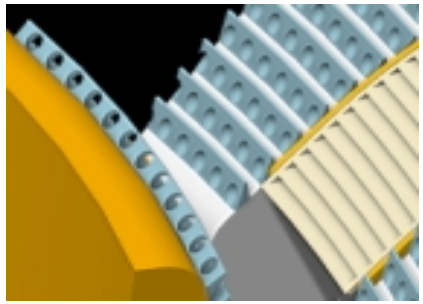
## Li, Sn Design

- Higher thermal conductivity helps
- MHD effects may change penetration geometry
- Low recycling (for Li) may require He pumping at low pressure, (i.e. bigger ducts)

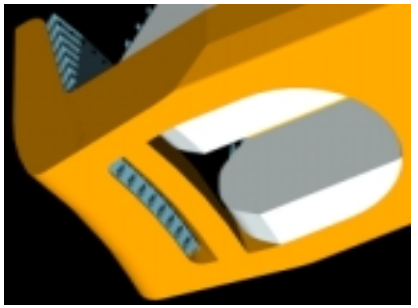
# Divertor Cassette Configuration

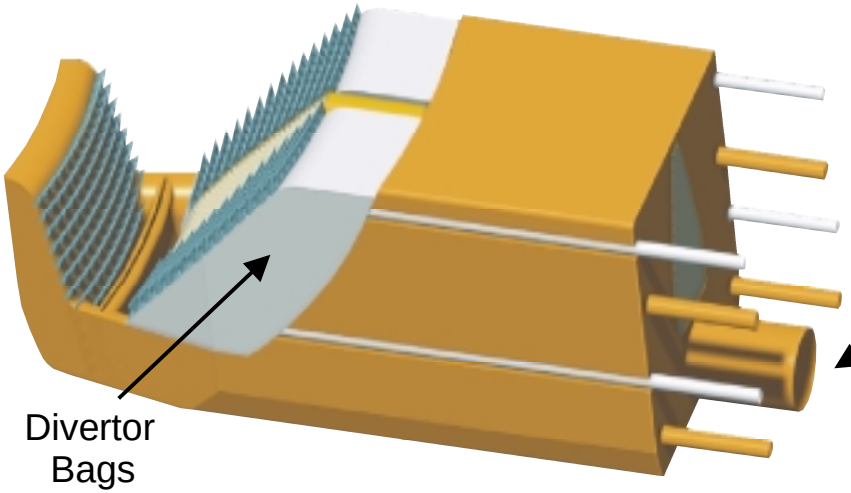



Close-up of flow disruption baffles

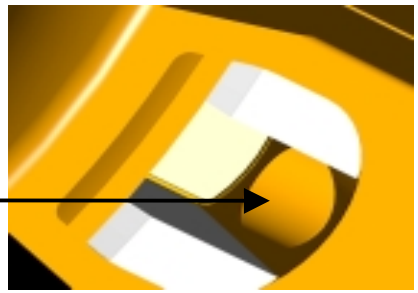


Underneath view showing fast flow drain passages





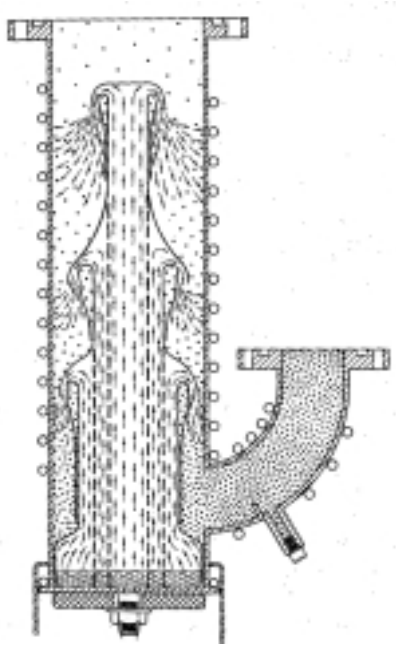

Vacuum Pumping Duct

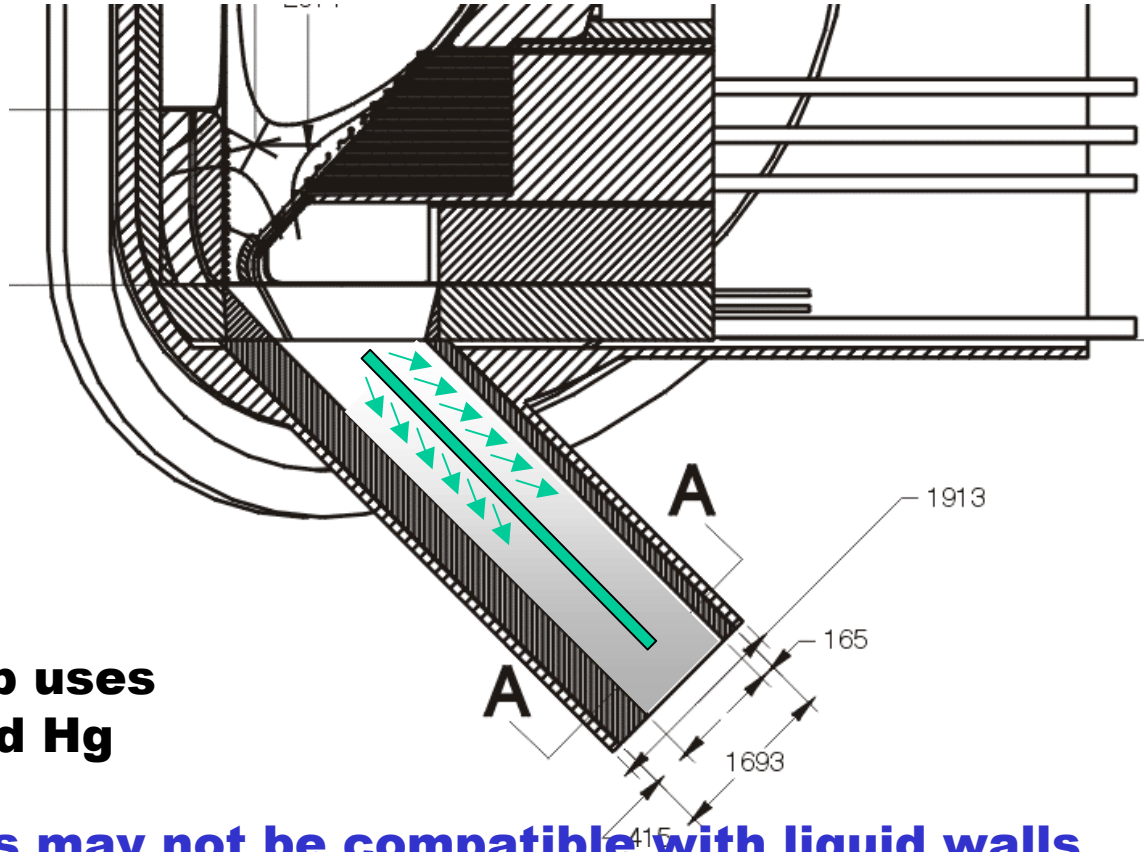


ornl

UT-BATTELLE

# Can liquid be used as diffusion pump?





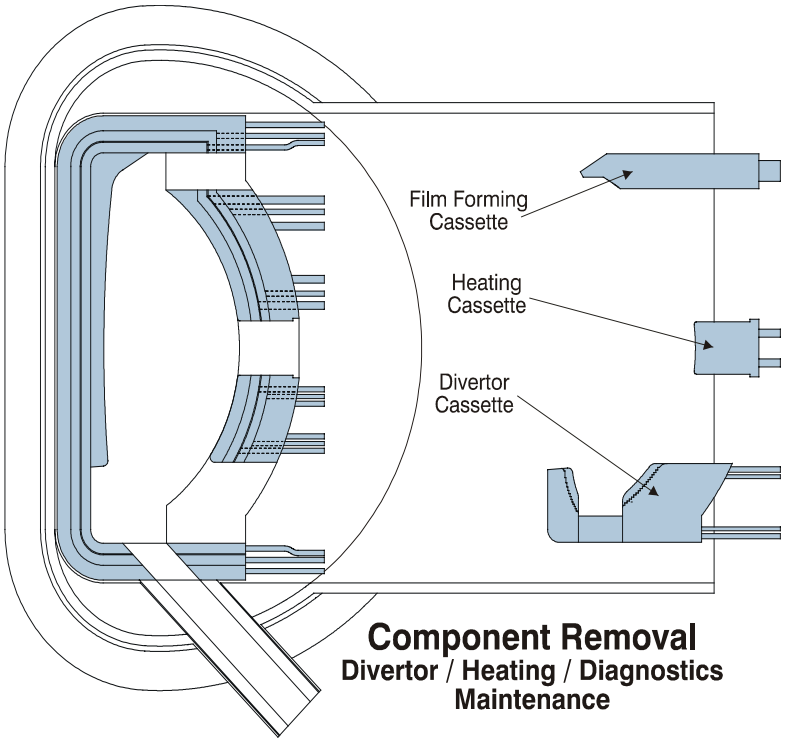

**Typical diffusion pump uses oil, older pumps used Hg**

- **Conventional pumps may not be compatible with liquid walls**
- **Need compression ratio ~ $10^2$ - $10^3$**
- **Can liquid velocity be high enough for concept to work?**

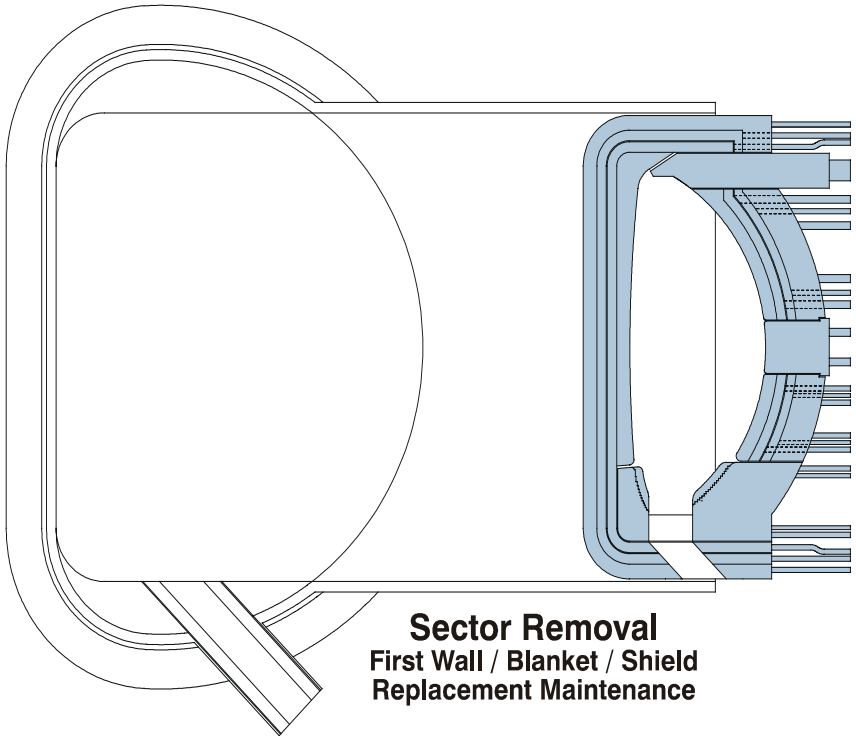
ornl

UT-BATTELLE

# Maintenance Concept




**High Maintenance Components**
**(Individual Cassette Removal)**




**Low Maintenance Components**
**(Requires Total Sector Removal)**

# Tradeoffs among parameters

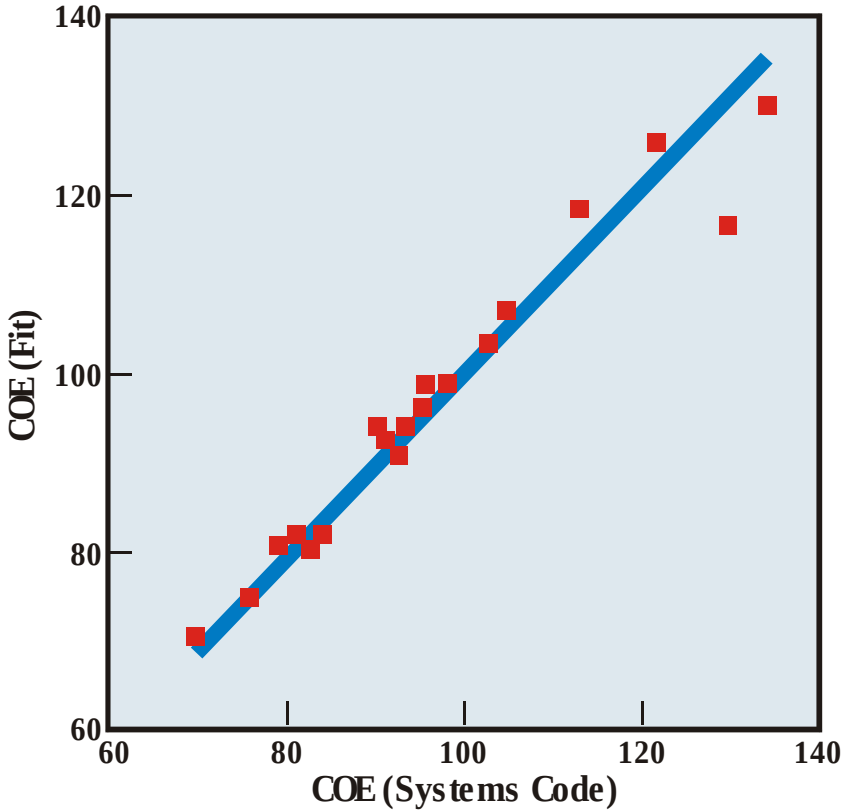
## Ward, et al of UKAEA developed simple relationship for COE based on system code studies of tokamak power plants

$$COE \propto \left(\frac{DF}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4}\, \nu_N^{0.4}\, N^{0.3}}$$

**Apart from economic variables, an order of merit for reducing the cost of electricity is:**

**(1) Availability**
**(2) Thermodynamic Efficiency**
**(3) Unit Size**
**(4) Normalized $\nu$**
**(5) Limiting Density**

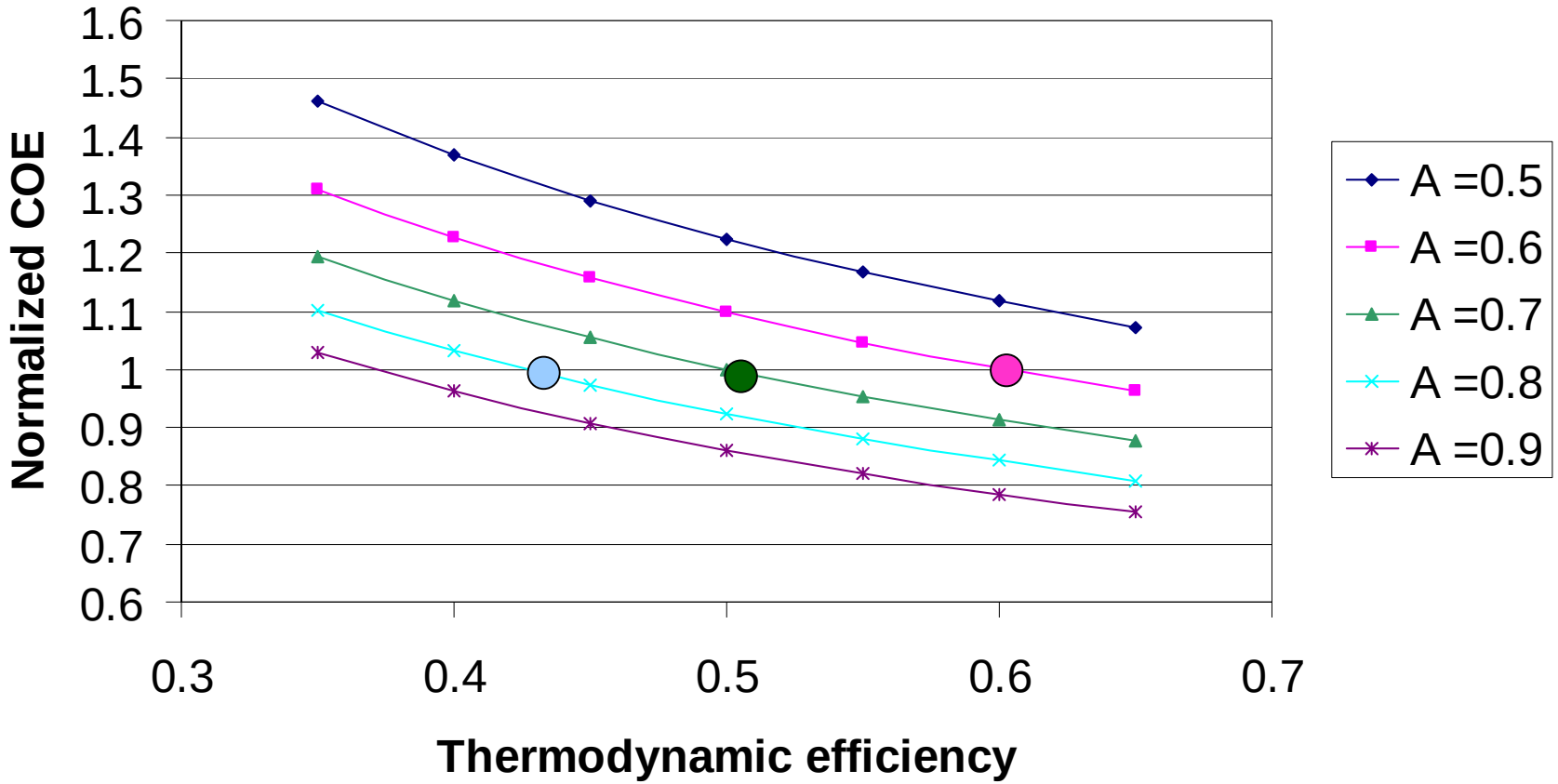
This work was funded by the UK Dept. of Trade and Industry and by EURATOM



# $\eta_{thermal}$ and Availability

## COE vs thermodynamic efficiency

**for various values of availability, normalized to η-therm = .5, A =.7**



# Summary

- **The CliFF liquid wall concept has been integrated into the ARIES-RS reactor design using Flibe for both the FW and blanket coolant**

- **CliFF system consists of:**
  - Convective layer-forming / fast flow cassette
  - Divertor cassette with integrated penetration for heating/diagnostics
  - Integrated drain and vacuum pumping duct
  - Piping for all coolant circuits
  - Full sector maintenance for everything but film former, divertor, and penetration cassettes, which can be independently replaced

- **The configuration also uses woven SiC "bag" structures in place of conventional blankets and shielding**

- **Changes to the the configuration are being assessed to replace Flibe with a liquid metal (probably Sn) for the fast flow and Pb-Li or Flibe for the blanket**
  - MHD effects
  - Material compatibility
  - Tradeoff between availability and efficiency

# Plans for FY 01

## Excerpt from FY-01 work plan for Task III:

### III.1 Mechanical Design, Maintenance, Integration

- Document requirements and system parameters (ORNL)
- Develop and update configuration layout and CAD models based on input from other subtasks, including pumping, divertor, inlet and exit nozzles, piping, maintenance approach, etc.(ORNL)
- Define penetrations for heating, fueling, etc. (ORNL)
- Define 3-D magnetic field along piping, flow trajectories (ORNL)
- Conducting shell and other liquid-bulk plasma considerations (PPPL-Kaita et al, TBD,UCSD-ARIES)