Recent Progress in the APEX Program on

ARIES/CLIFF Molten Salt Chamber Design

(flowing liquid Flinabe wall and blanket)

Presented by **Richard Nygren**
on behalf of the **APEX Team**

principal contributors:

R.E. Nygren, Sandia National Laboratories
D.K. Sze, University of California, San Diego
C. Eberle, P.J. Fogarty, Oak Ridge National Laboratory
T.D. Rognlien, M.E. Rensink, Lawrence Livermore National Laboratory
S.S. Smolentsev, M.E. Youssef, University of California, Los Angeles
M.Z. Sawan, University of Wisconsin
B.J. Merrill, Idaho National Energy and Environmental Laboratory
R. Majeski, Princeton Plasma Physics Laboratory

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, Department of Energy under Contract DE-AC04-94AL85000.

What will make fusion work?
It's not just physics!

We may need innovative chamber technology

- to define an attractive vision of fusion, and
- to make a workable power plant.

Outline

- APEX Program - highlight design “roadmap”
- How liquid first wall works
- Flinabe and the radiative plasma edge solution
- Flinabe liquid chamber design

(upcoming special issue for Fusion Eng. & Design)

APEX and ALPS are US programs on liquid wall technology.

APEX (Prof. Mohamed Abdou, Dir.) – advanced chamber technology

- Experiments and engineering science of free surface liquid flows
- (subset) MHD controlled free surface flows
- Interdisciplinary tasks (e.g., PSI & plasma-wall electromagnetic interactions)

- Design of liquid wall fusion chamber
  - *chamber design (Sze et al.)*
  - *divertor design integration (Nygren et al.)*
- Design of solid wall fusion chamber *(Wong et al.)*

APEX and ALPS are US programs on liquid wall technology.

APEX (Prof. Mohamed Abdou, Dir.) – advanced chamber technology

-
-
- Design of liquid wall fusion chamber
  - *chamber design (Sze et al.)*
  - *divertor design integration (Nygren et al.)*
-

ALPS (Dr. Jeff Brooks, Dir.) – advanced PFCs (plasma facing components)

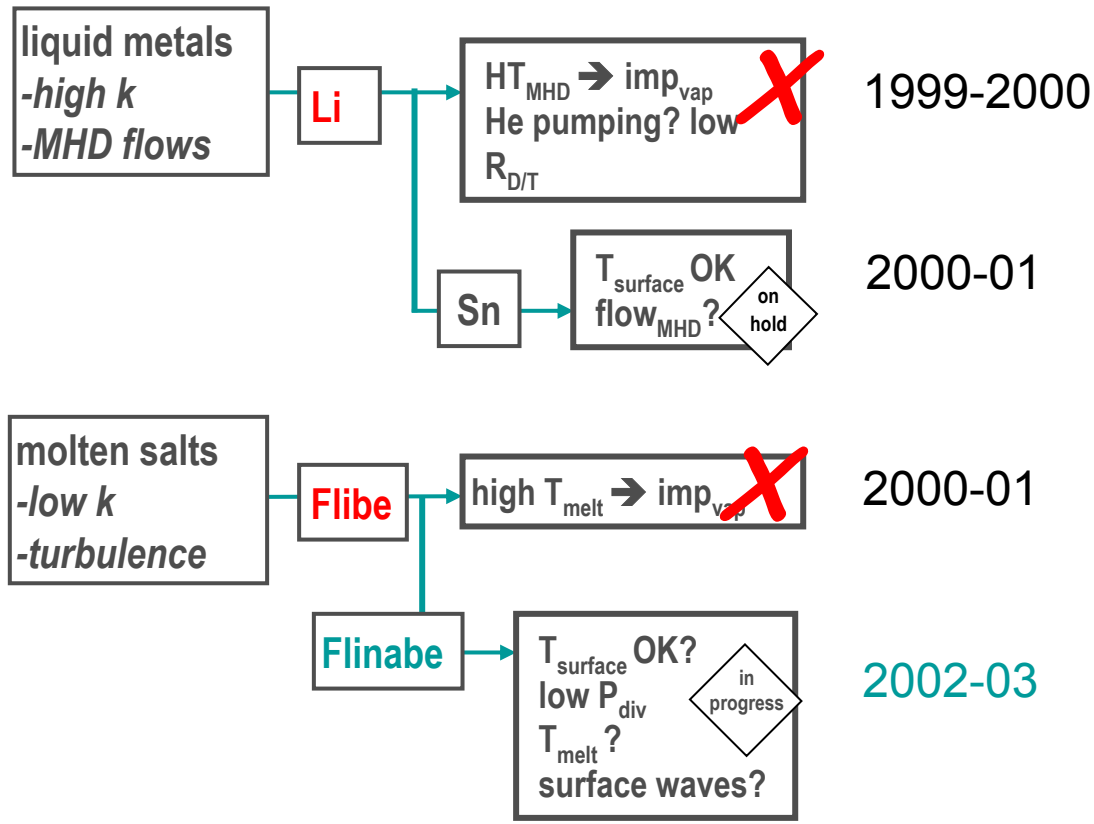
- Plasma surface interactions with liquid surfaces
- Experiments to support "next-generation" applications

ALIST (Dr. Mike Ulrickson, Dr. Alice Ying, co-leaders) – NSTX Li module

We are investigating liquid metals and molten salts.

ARIES-RS
configuration
- **16 TF coils**
- **5.5m, R**
- **4 aspect ratio**

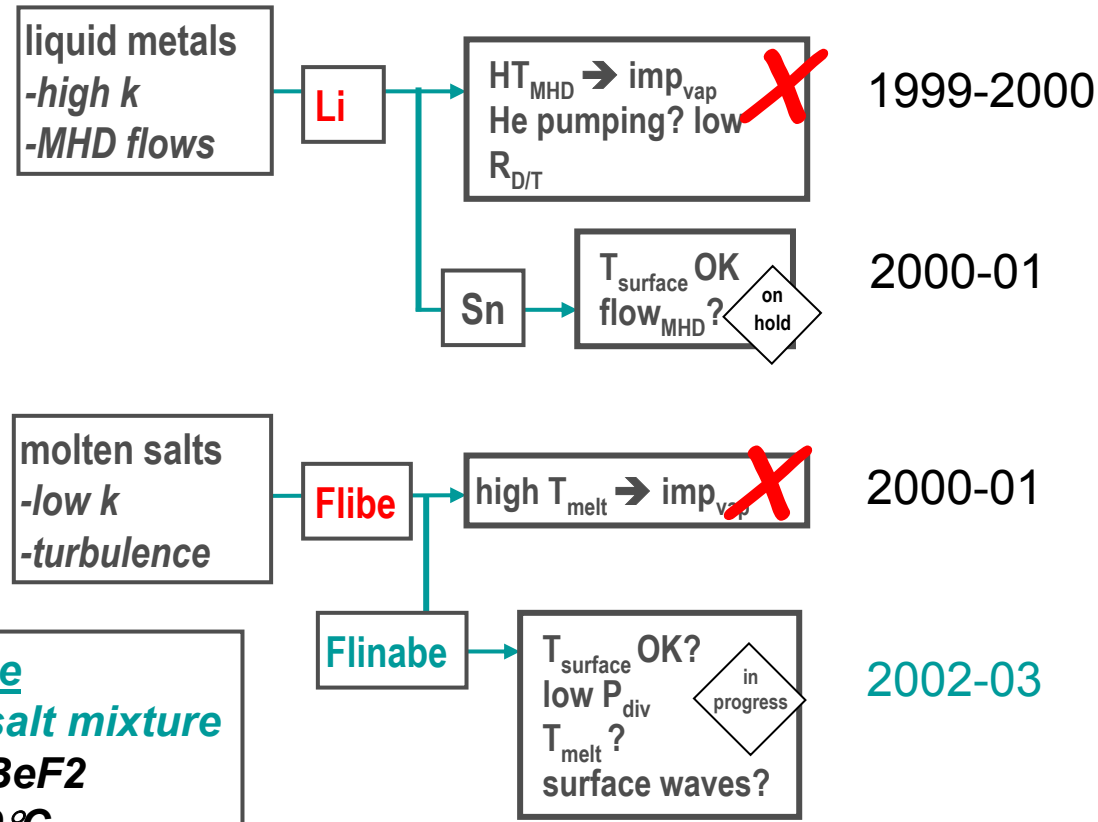
P_{fusion} (2170)
→3840MW
to define
heat loads



We are investigating liquid metals and molten salts.

ARIES-RS
configuration
- 16 TF coils
- 5.5m, R
- 4 aspect ratio

P_{fusion} (2170)
→3840MW
to define
heat loads



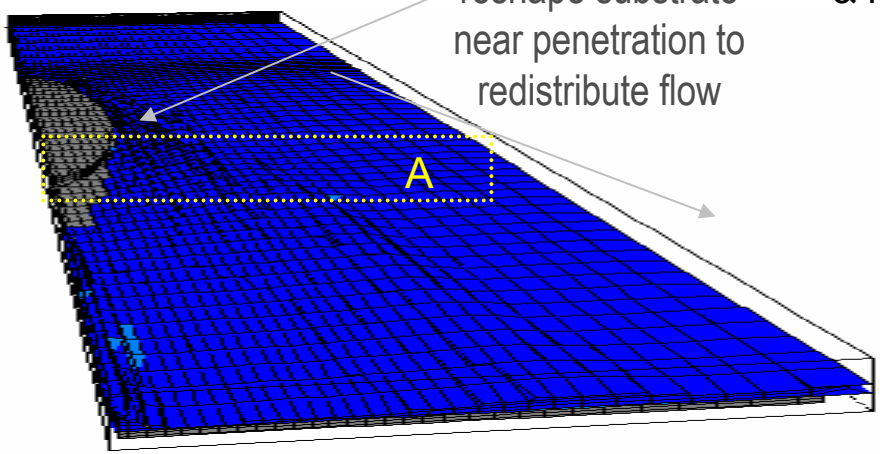
Flinabe
ternary molten salt mixture
LiF-NaF-BeF2
Tm>300℃
More data needed.

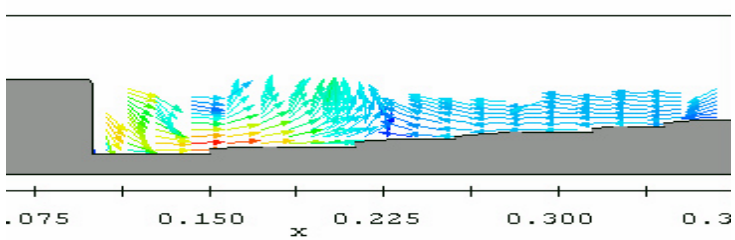
Some innovative ideas

Flow around penetrations

Karani Gulec, UCLA

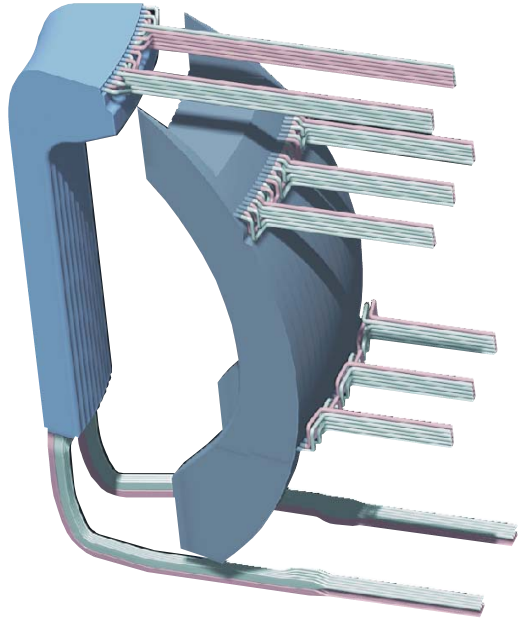
reshape substrate near penetration to redistribute flow

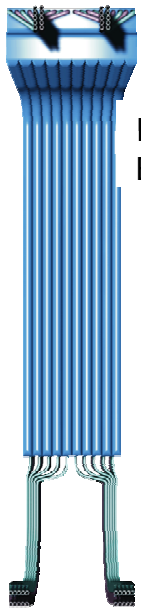




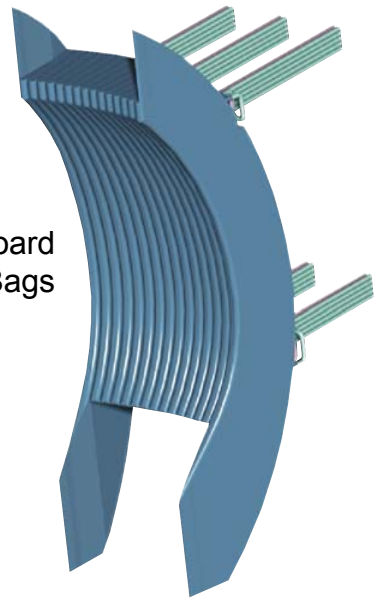
Flexible SiC cloth blanket bags

Brad Nelson & Paul Fogarty ORNL





Inboard Bags



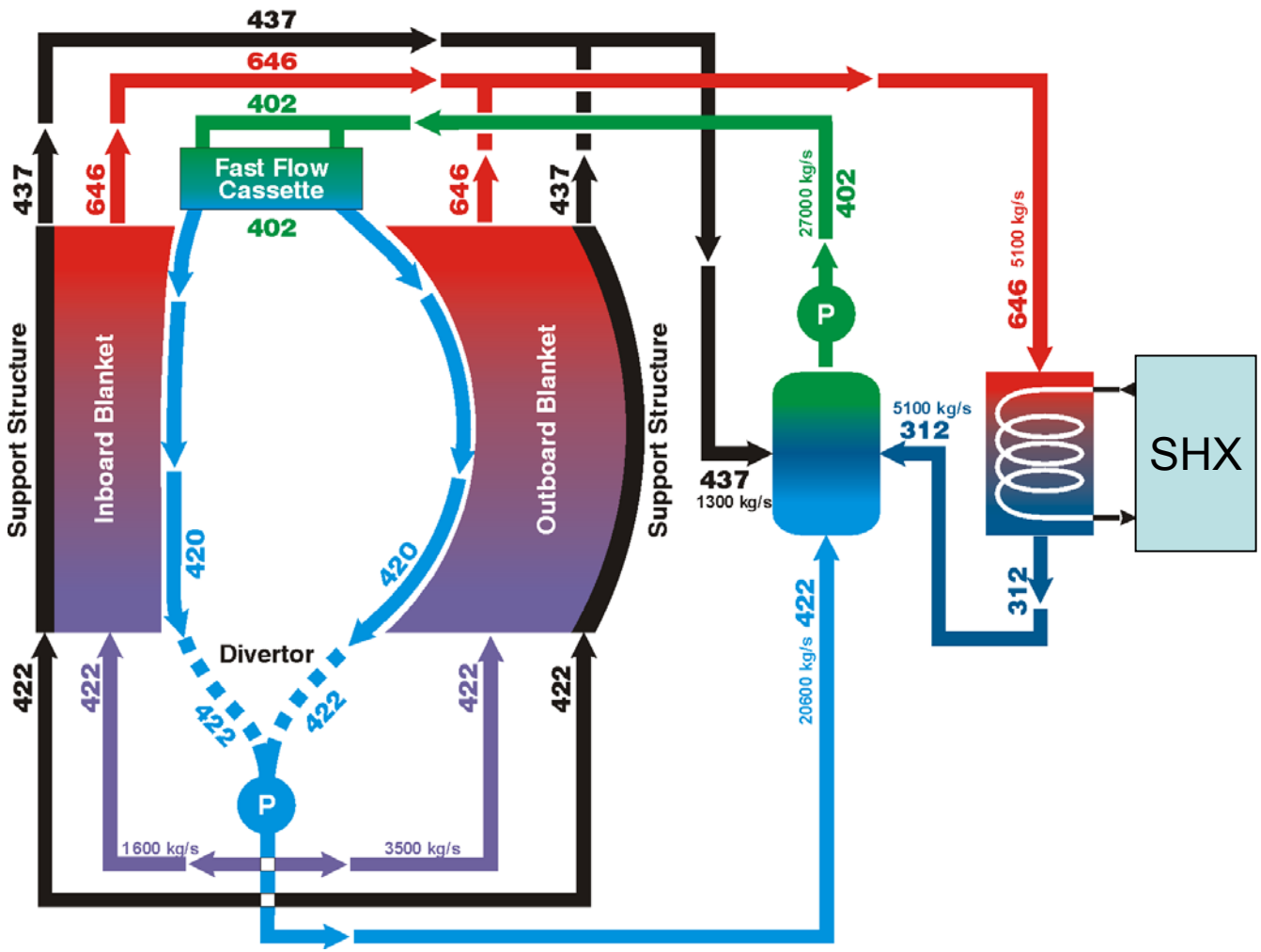
Outboard Bags

Outline

- APEX Program - highlight design “roadmap”
- How liquid first wall and blanket work
  - Thin wall (2cm) but large flow rate, so flow recycles.
  - Slow blanket flow, Flinabe heats from 422 to 646°C.
  - Self protecting jets inject liquid first wall.
- Flinabe and the radiative plasma edge solution
- Flinabe liquid chamber design

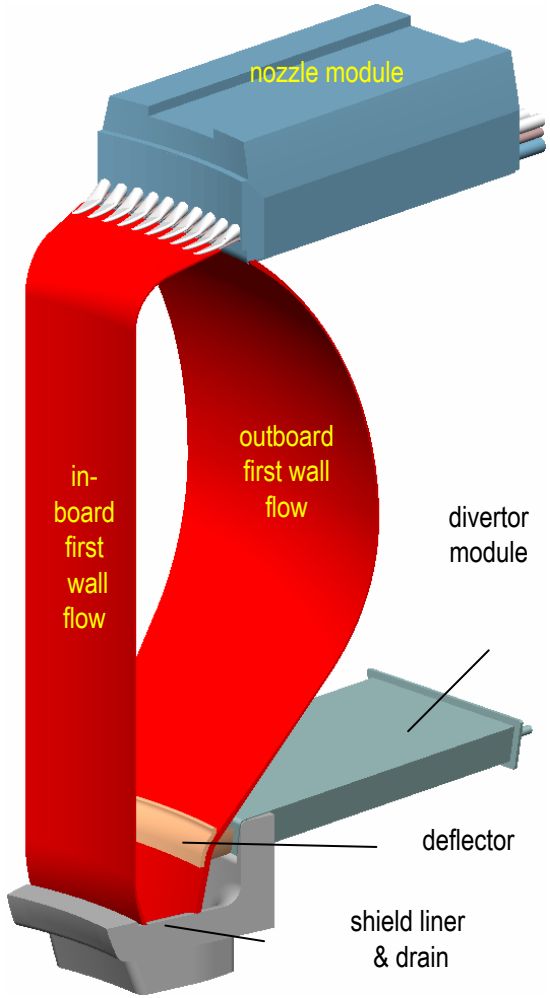
(upcoming special issue for Fusion Eng. & Design)

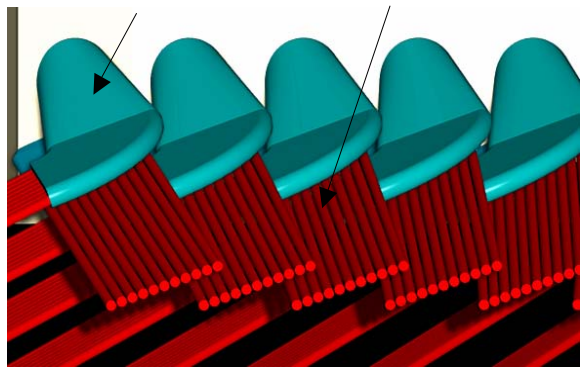
Fluid power flow for Flinabe ARIES/CLIFF Design

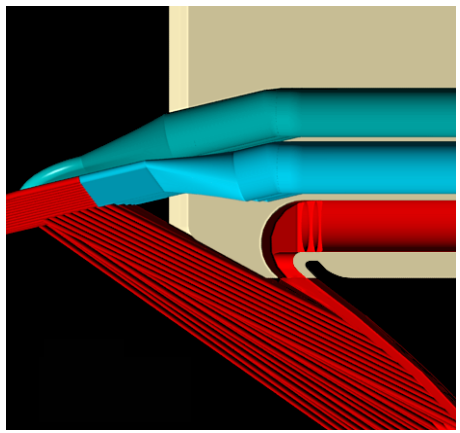


"Self-shielding" jets provide first wall flow.

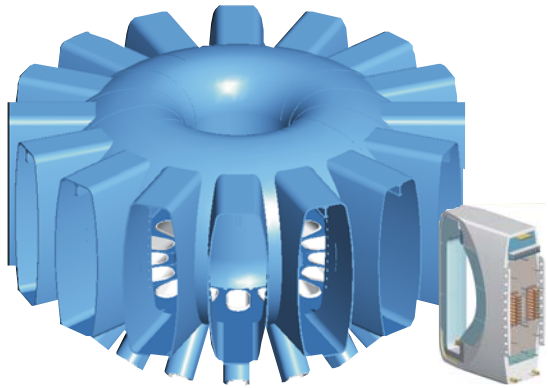
(Also another innovative idea from ORNL - CAD drawings by PJ Fogarty)

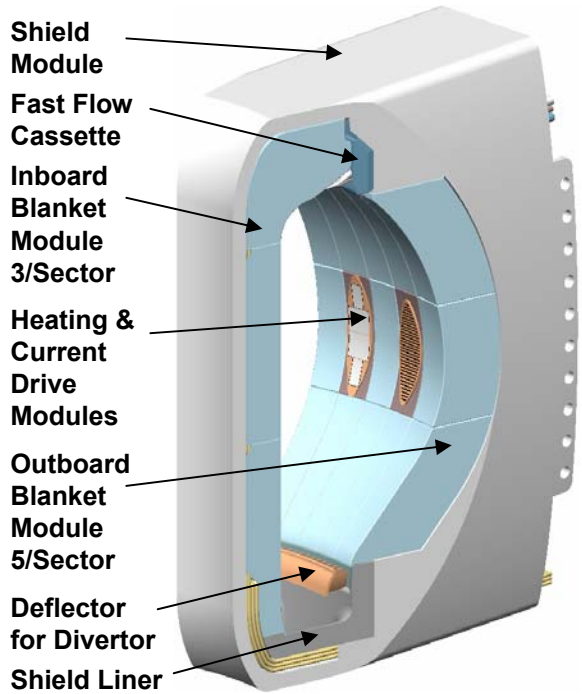


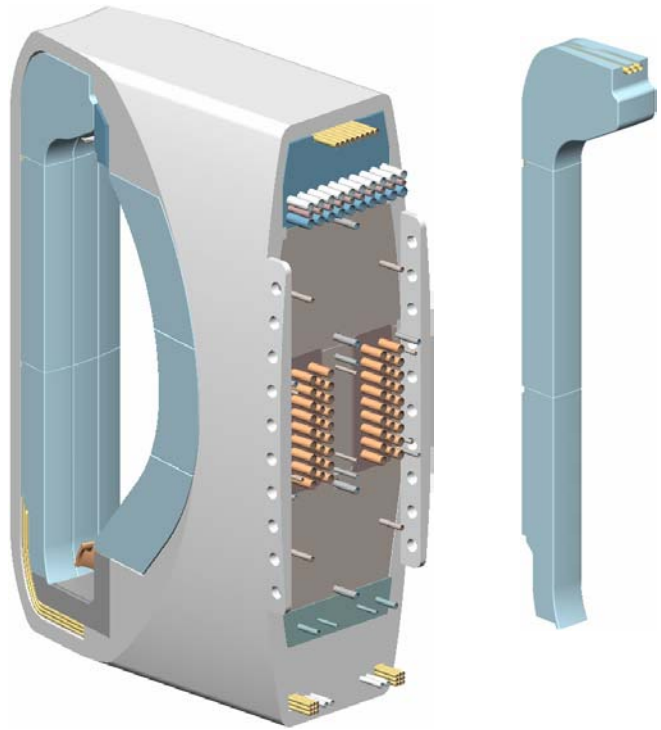




Blanket & Shield Modules

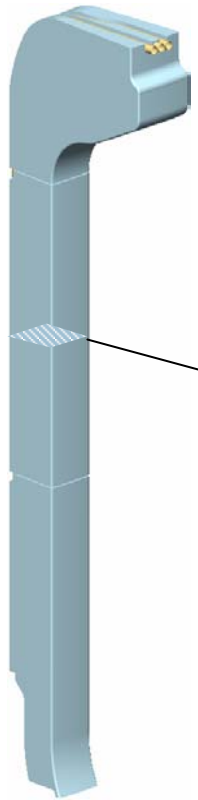


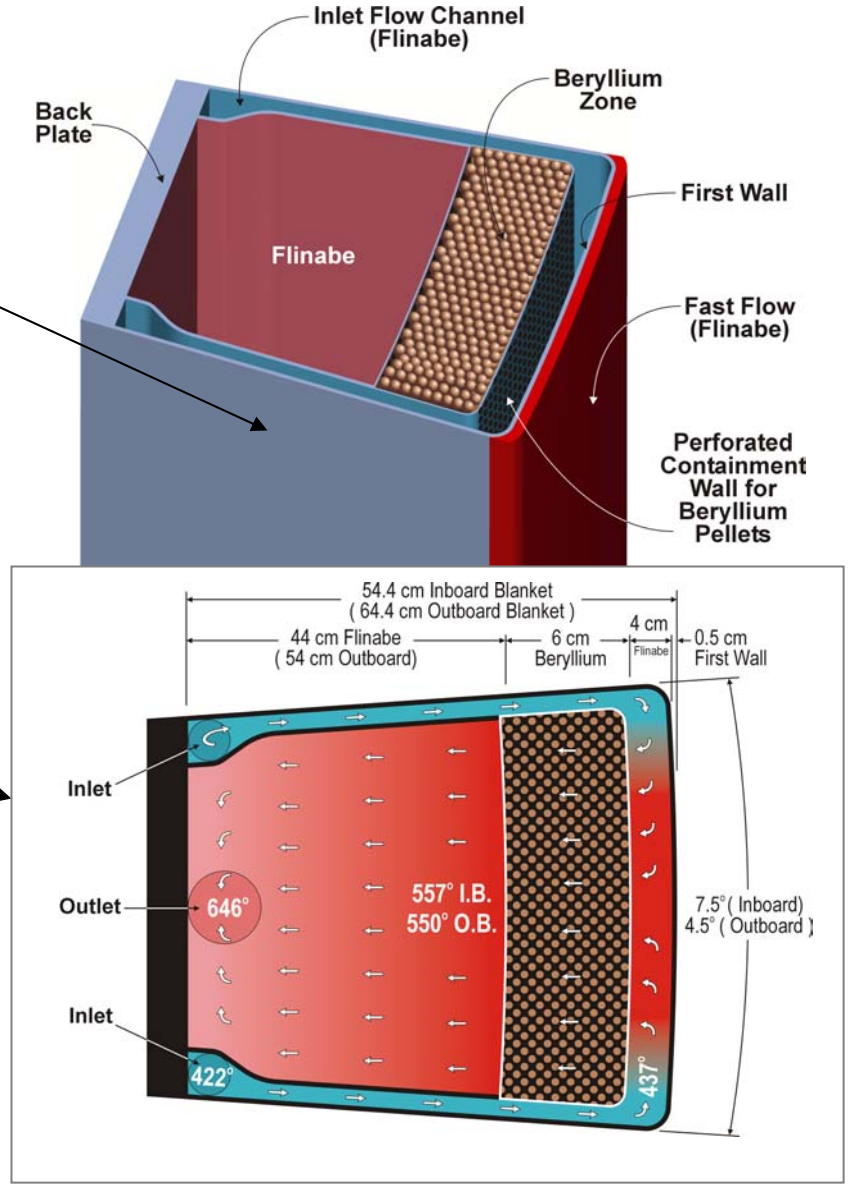




Blanket Modules

Advanced Ferritic Steel
"nano-dispersed" carbides





Outline

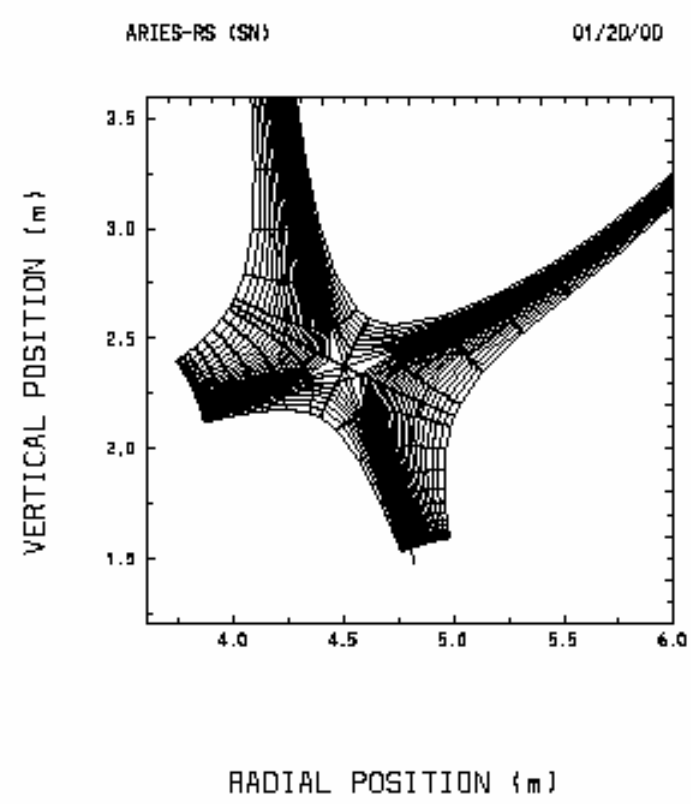
- APEX Program - highlight design “roadmap”
- How liquid first wall works
- Flinabe and the radiative plasma edge solution
- Flinabe liquid chamber design

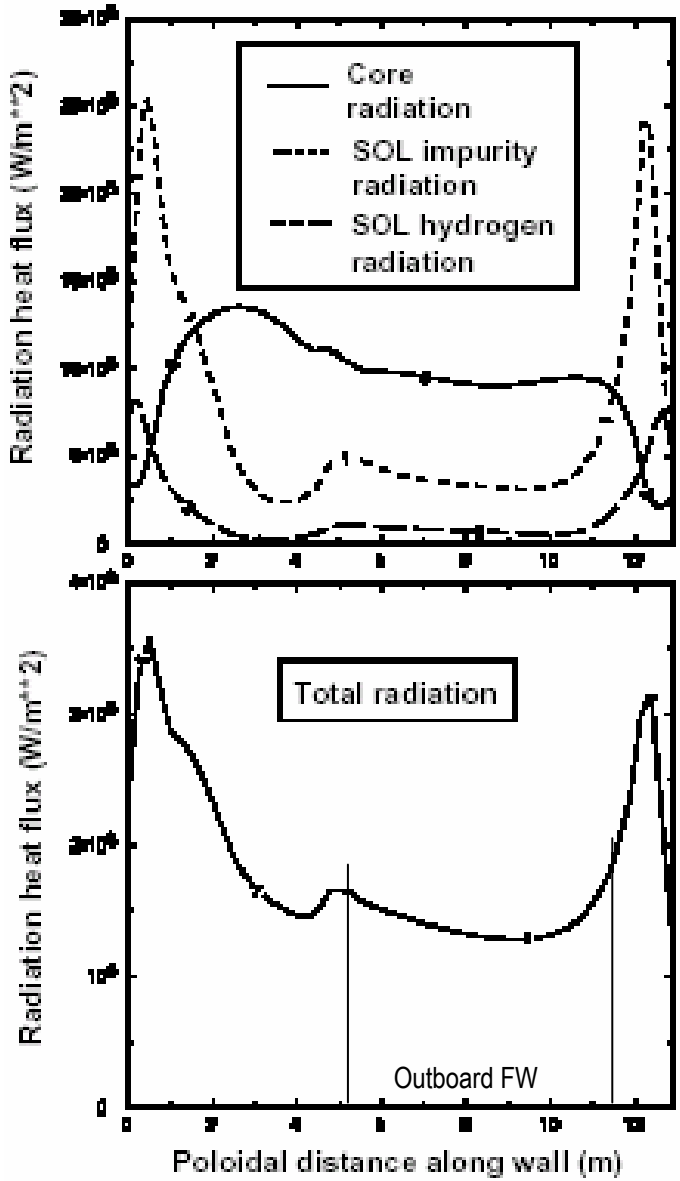
(upcoming special issue for Fusion Eng. & Design)

- 3840MW gives 768MW P_{α} also 142MW $P_{auxiliary}$
- HPD dilemma; P increase, area & λ-q decrease
- must radiate power
- Can plasma tolerate high edge radiation?

Plasma Edge Modeling

Tom Roglien & Marv Rensink, LLNL use 2-D UEDGE model to estimate heat loads for first wall and divertor and must develop stable plasma solutions.





Colorized plots of flourine radiation show stable window

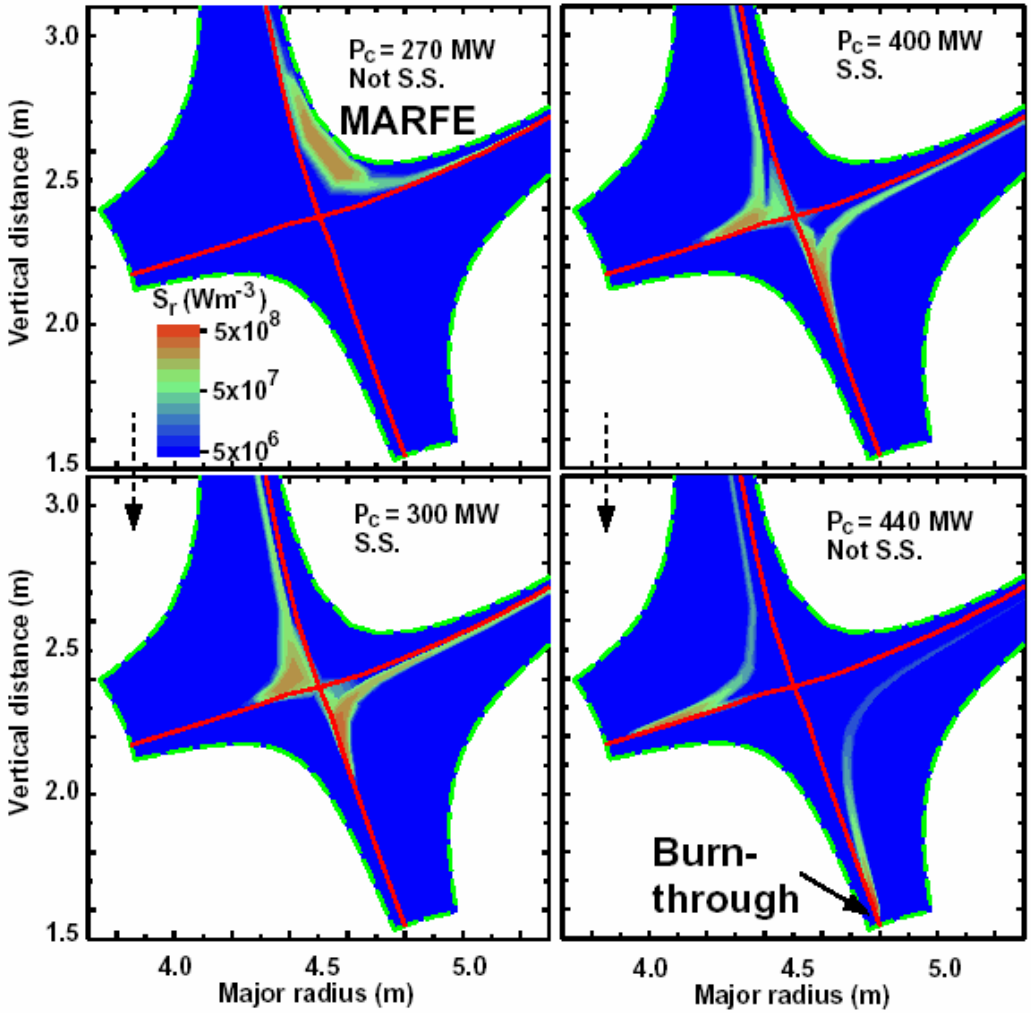
P_c is power convected from core into edge.

Four plots show similar conditions with progressively higher P_c.

Middle cases (300 & 400MW) are stable.

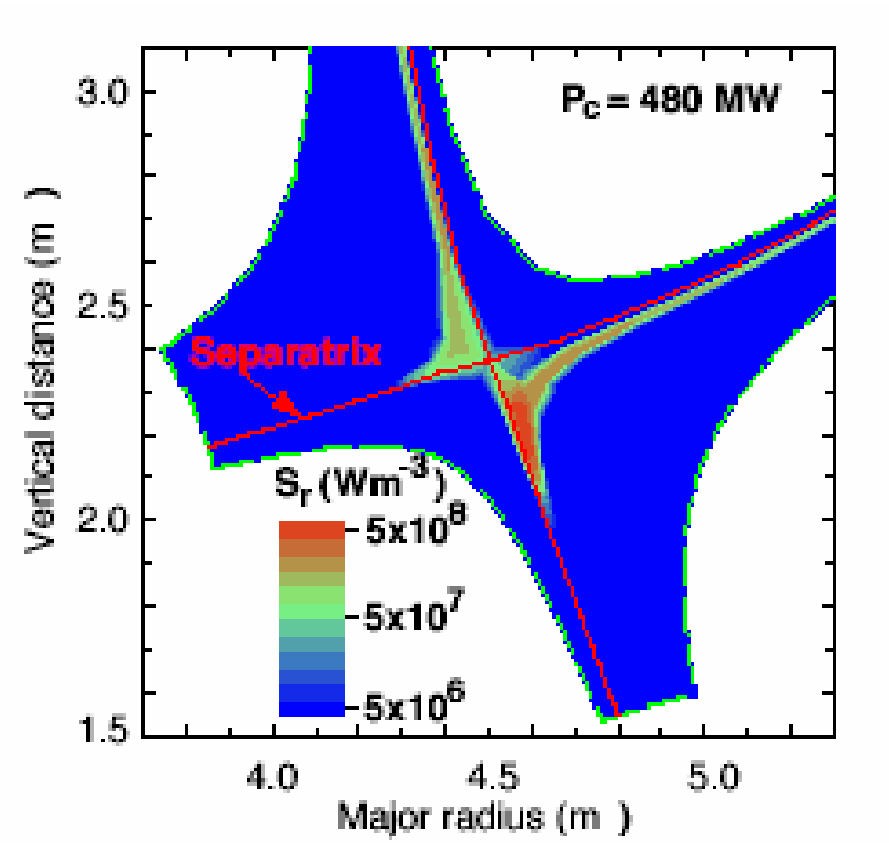
Uses input from WBC Code by Jeff Brooks, ANL, for sputtering with sheath effects.

Plots courtesy Roglien & Rensink, LLNL



Colorized plots of flourine radiation show stable window

- *Later case with different Flinabe temperatures*
- *Core radiation, 430MW*
- *764MW to FW*
- *144MW to divertor (only)*



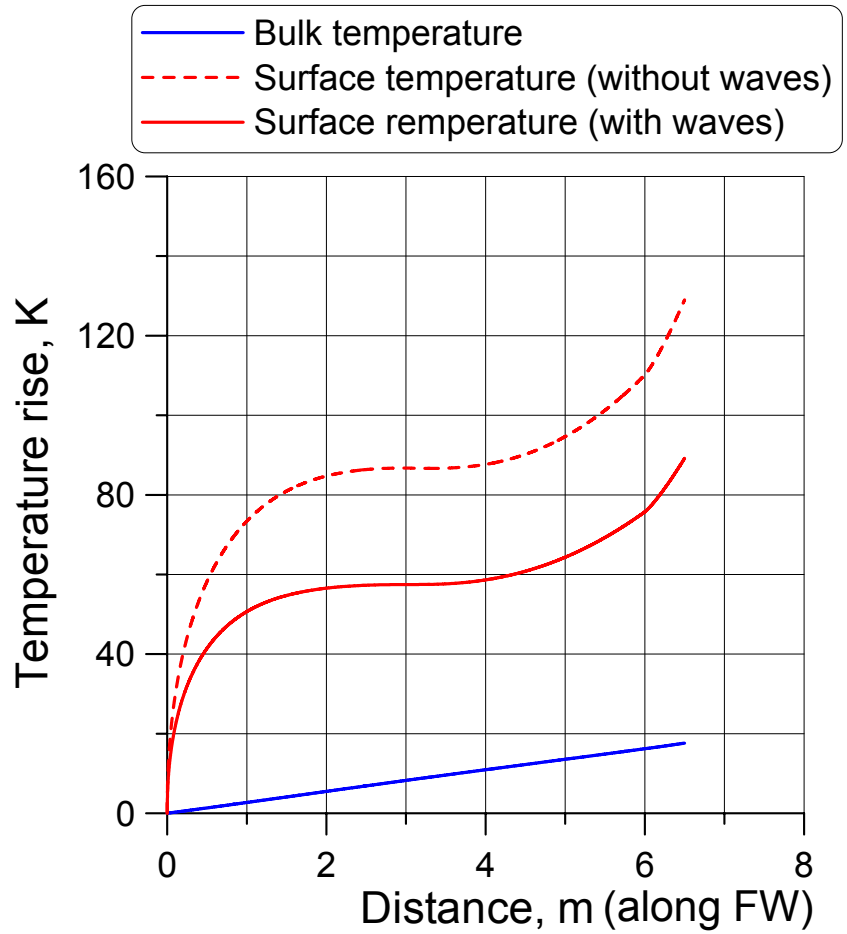
Plot courtesy Roglien & Rensink, LLNL

First wall heat transfer model includes MHD effects on turbulence

Heat transfer model by Sergey Smolentsev, Neil Morley & (student) Brent Freeze, UCLA, is modified k-ε type and includes (separately)

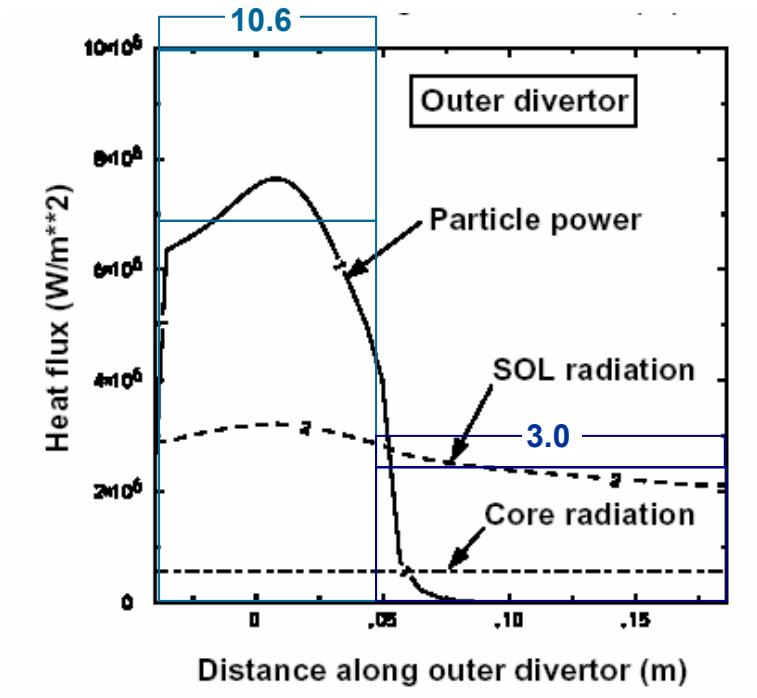
- **MHD effects on turbulence**
- **effects of surface waviness**

Plot courtesy of Smolentsev, UCLA

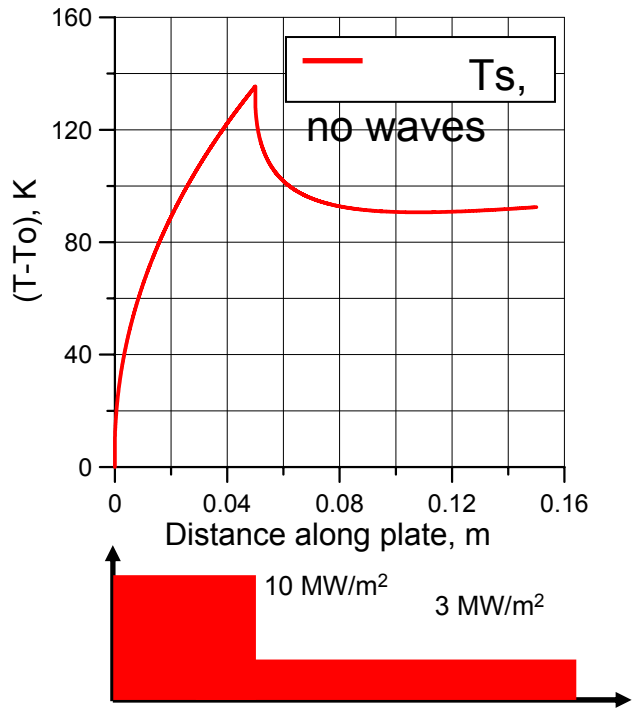


With low peak heat load in divertor Flinabe temperature is OK.

Divertor heat load from Roglien & Rensink, LLNL

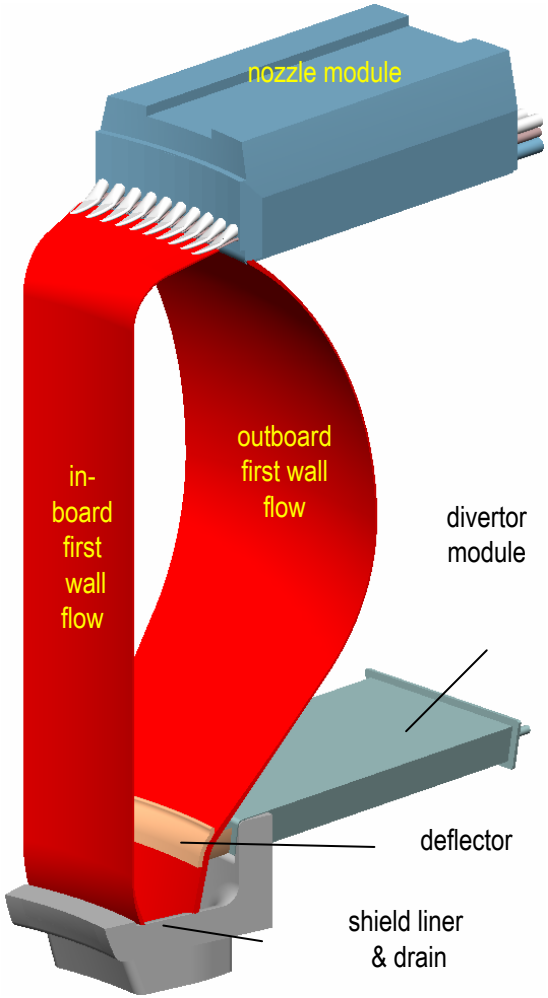


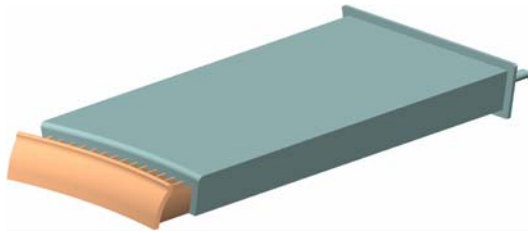
Result from Smolentsev, UCLA

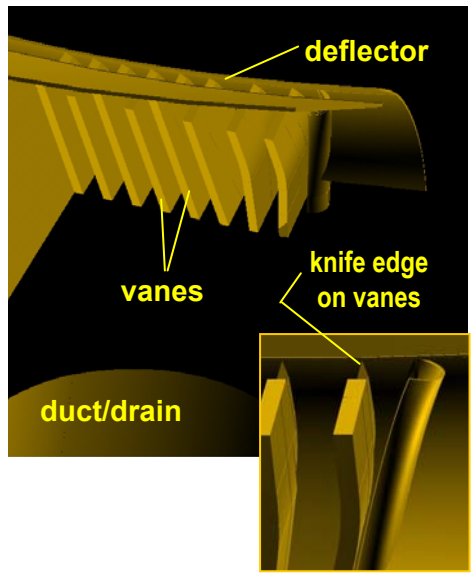


Temperature rise of Flinabe in divertor vs. distance along flow.

Divertor deflector redirects flow and thermally mixes fluid.

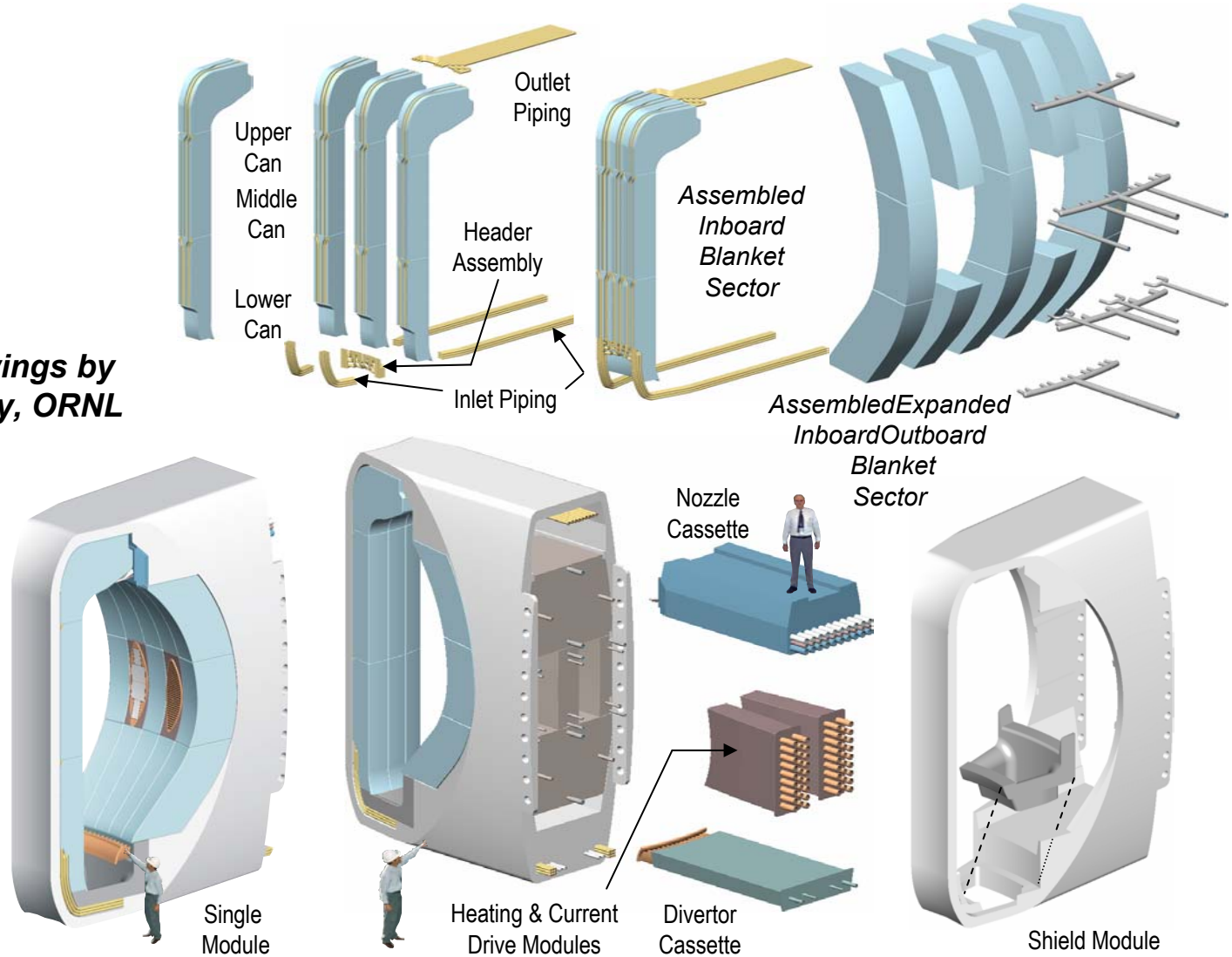




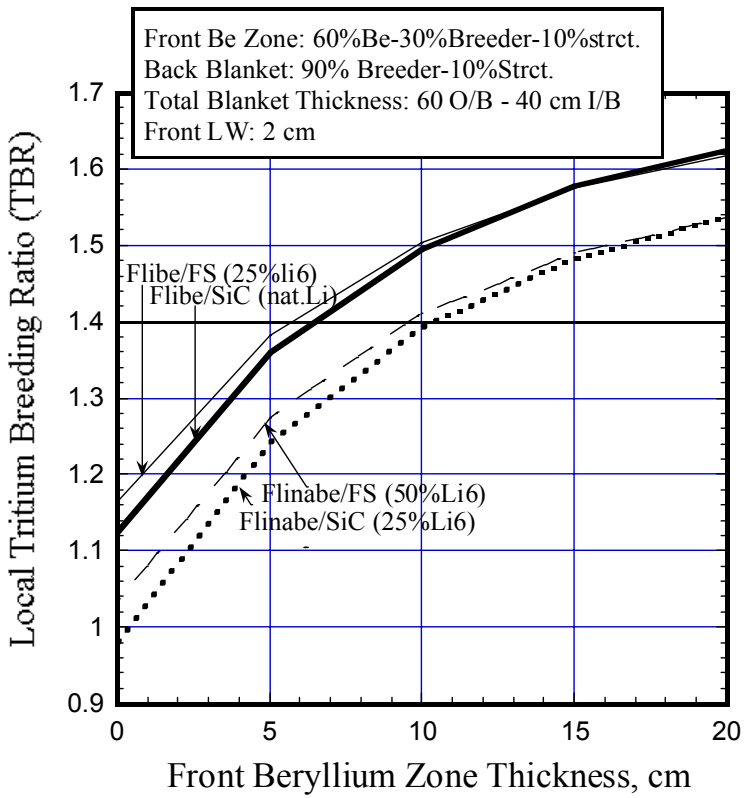


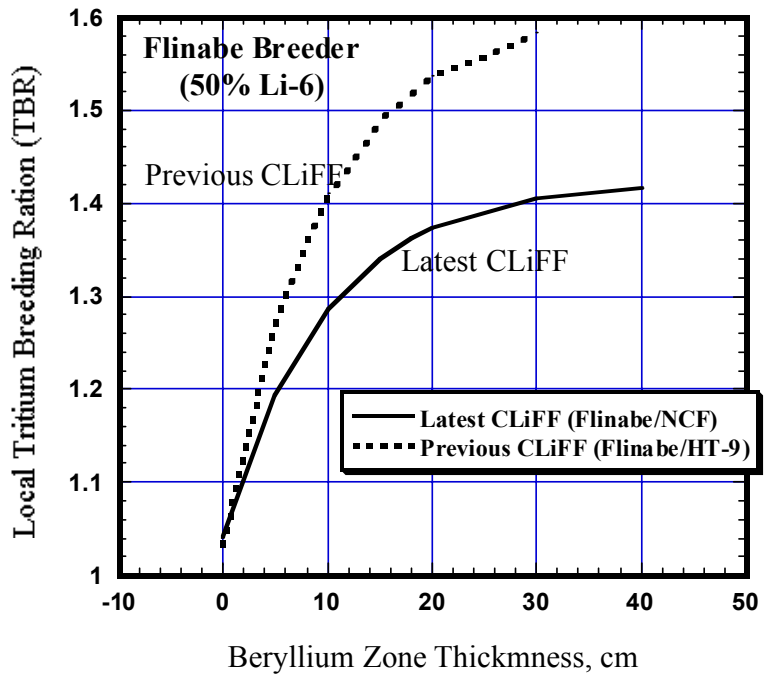
Mechanical configuration and assembly was developed by ORNL.

CAD drawings by PJ Fogarty, ORNL



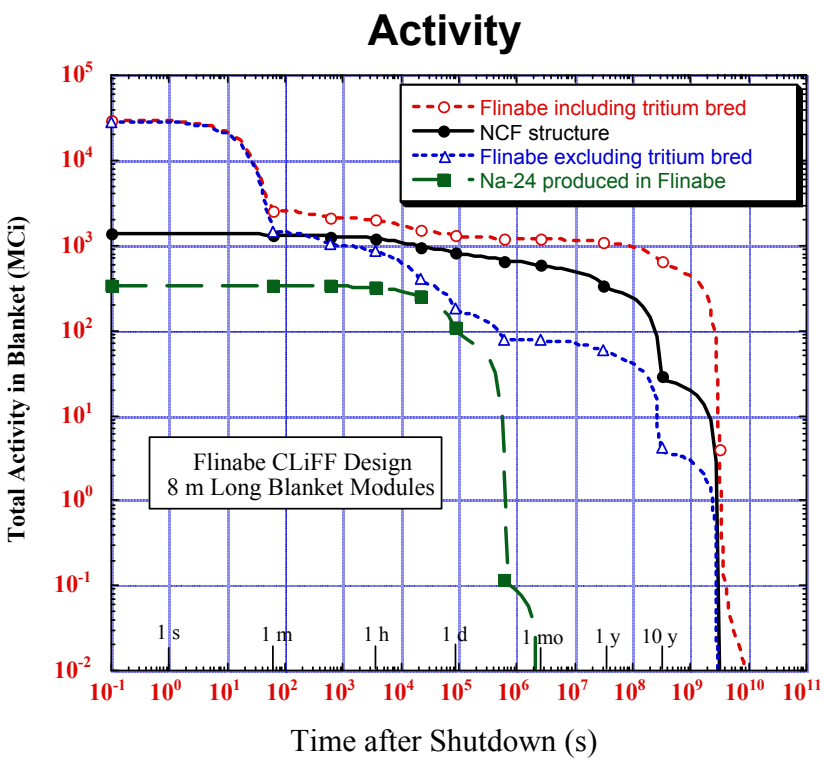
Tritium breeding calculations were redone for AFS structure.

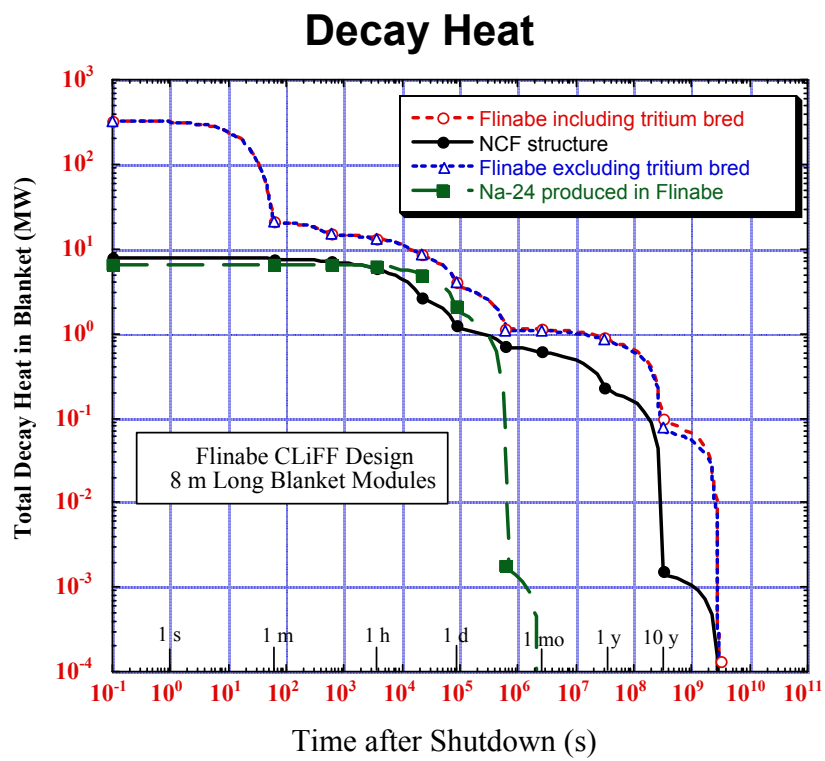




Results of work by Mahmoud Youssef, UCLA.

Rad waste calculations were redone for AFS structure.





Results of work by Mohamed Sawan, U. Wisconsin

Other items

Tritium solubility in Flinabe is low. Therefore recovery is easy but high partial pressure means permeation of tritium is an issue.

- **Tritium recovery from Flinabe is by gas purging; a vacuum disengager process is proposed; a key step is using a vacuum system to pump tritium from the molten salt. (proposed for Flibe and can be used with Flinabe)**
- **Permeation concern leads to ceramic barrier in PHX and use of secondary heat exchanger for isolation and further tritium collection.**

(tritium system work by Dai Kai Sze, UCSD)

- **Safety evaluation was performed using MELCOR Code.**

(tritium system work by Brad Merrill, INEL)

Closing

- Secial Issue of Fusion Engineering & Design for APEX will have overview article on Flinabe design (draft is ~60 pages). Issue will also have articles onj diverftor integration, heat transfer modeling, MHD experimentsand modeling and more.
- Flinabe chamber design is startling and pleasing result. The need to identify plasma edge solutions and manage the divertor heat load led to a low and acceptable peak power in the divertor and a higher but manageable power load to the first wall.