Three-Dimensional Neutronics Assessment of Dual Coolant Molten Salt Blankets with Comparison to One-Dimensional Results

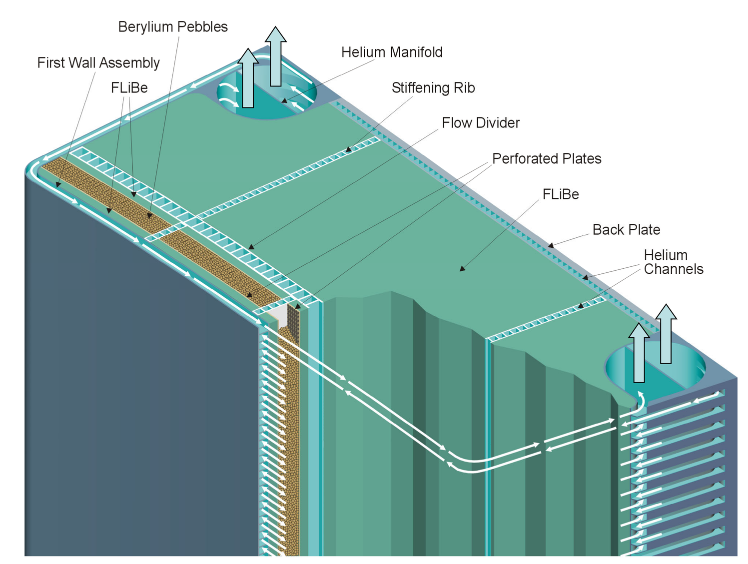
Mohamed Sawan
Fusion Technology Institute University of Wisconsin, Madison, WI

Mahmoud Youssef
University of California, Los Angeles Los Angeles, CA

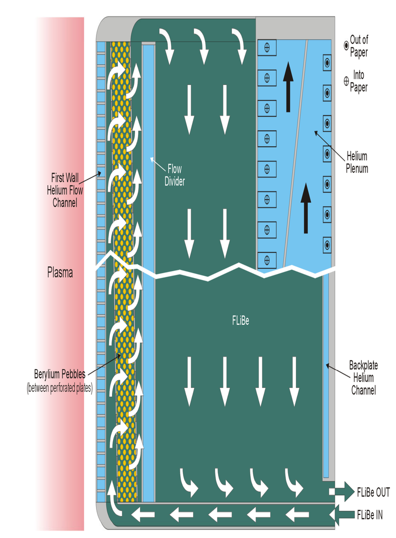
Background

- For U.S. Advanced Power Plant design we assessed blanket design concepts based on use of reduced activation ferritic steel (F82H) as structural material and liquid breeders as coolant and tritium breeder
- Evaluate concepts that can be developed, qualified, and tested in the time frame of ITER
- Blanket designs with molten salts (MS) have been assessed
- Flibe has attractive features of low activation, low chemical reactivity with air and water, low electrical conductivity, and good neutron attenuation properties. However, it has a relatively high melting point (459°C), low thermal conductivity, tritium permeation concern, requires control of the corrosive TF and F_2, and need separate neutron multiplier

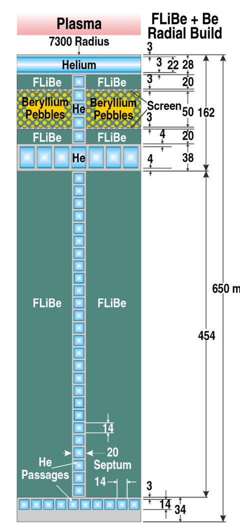
Dual-Coolant Design Configuration



Poloidal Cross Section



Radial Build



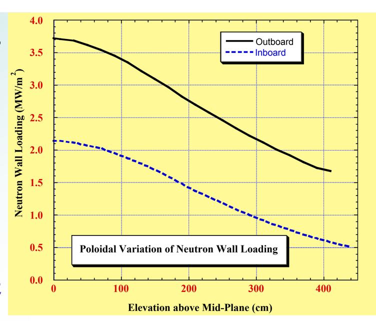
Dual-Coolant Concept has Attractive Features

- An attractive design option was identified based on the dual coolant (DC) concept with helium cooling the FW and blanket structure, Flibe breeder, and Be neutron multiplier
- The low electrical conductivity of MS minimizes impact from the MHD effects without the need for separate MHD insulator in the coolant channels
- The low thermal conductivity of MS together with suppression of turbulence by the magnetic field reduce the heat losses from the breeder to the actively cooled steel structure, allowing MS bulk temperatures higher than the structure temperature with the potential for higher power plant performance
- Performance of the DC concept with Be multiplier investigated with low melting point Flibe ($LiBeF_3$) and Flinabe to avoid the need for ODS steel coating and eliminate molten salt freezing

Reactor Parameters

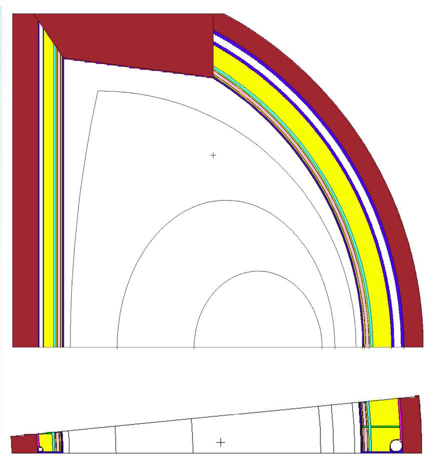
- Fusion power 2116 MW
- Major radius 5.8 m
- Aspect ratio 2.6
- Minor radius 2.23 m
- IB FW at 3.47 m @ midplane
- OB FW at 8.13 m @ midplane

- NWL distribution from 3-D calculations
  - Peak OB NWL 3.72 MW/m^2
  - Top/bottom OB 1.8 MW/m^2
  - Average OB NWL 2.66 MW/m^2
  - Peak IB NWL 2.14 MW/m^2
  - Top/bottom IB 1.1
  - Average IB NWL 1.33 MW/m^2
  - Average chamber NWL 2.13 MW/m^2

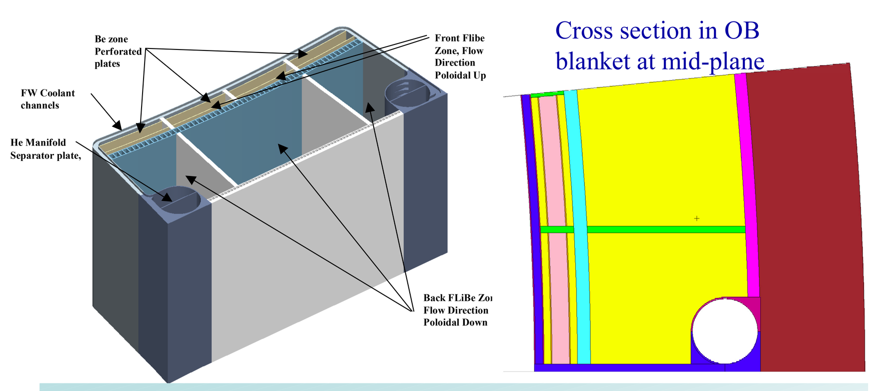


3-D Neutronics Modeling

- 3-D neutronics performed for the DC blanket with $LiBeF_3$ to check impact of 3-D geometrical effects and blanket heterogeneity on overall TBR and nuclear parameters
- Neutron source sampled from D-shaped plasma using a peaked distribution at magnetic axis
- The model includes detailed heterogeneous geometrical configuration of 40 cm IB and 65 cm OB blanket sectors
- 3-D model used a conservative assumption by including water-cooled steel (no breeding) with 1 cm tungsten armor in the double null divertor region (12% coverage)



3-D Calculation Procedure



- Used Monte Carlo code MCNP, version 5 along with nuclear data based on the FENDL-2 evaluation
- Because of symmetry only 1/128 of the chamber is modeled (1/4 of a sector) with reflecting boundaries
- One million source particles sampled and variance reduction techniques utilized to yield statistical uncertainties <0.1% in calculated overall parameters and <1% in local parameters

Differences between 3-D and 1-D Calculation Procedures

	3-D	1-D
Chamber model	Actual toroidal	Toroidal cylindrical
Plasma shape	Actual toroidal	Cylindrical extended infinitely in vertical direction
Source distribution	Actual peaked at magnetic axis	Uniform
Angular distribution of incident source neutrons	Mostly perpendicular to FW	Mostly tangential to FW
Refelection from chamber components	Accounted for correctly	No divertor

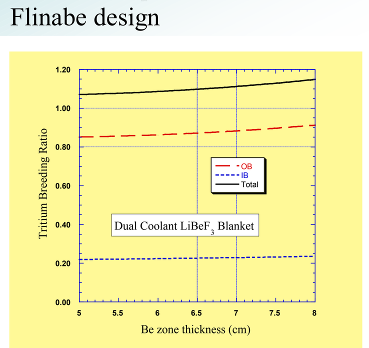
Tritium Breeding

- The lithium is enriched to 50% Li-6 in Flibe and 60% Li-6 in Flinabe
- The Be multiplier zone thickness is 5 cm with Flibe and 8 cm with Flinabe.

		Dual Coolant Flibe Blanket	Dual Coolant Flinabe Blanket
OB	Multiplier Zone	0.3613	0.4478
	Breeder Zone	0.4899	0.3958
	Total Outboard	0.8512	0.8436
IB	Multiplier Zone	0.1191	0.1436
	Breeder Zone	0.1002	0.0737
	Total Inboard	0.2193	0.2173
Total Overall TBR		***1.0705***	***1.0609***

- In the Flibe blanket, ~45% of tritium is breed in the multiplier zone
- ~56% of the tritium is bred in the thicker multiplier zone in the Flinabe design

- This is conservative estimate (no breeding in double null divertor covering 12%)
- Minor design modifications such as increasing Be zone and/or blanket thickness can be made to enhance TBR if needed. Increasing Be zone from 5 to 6 cm increases TBR to 1.09 for Flibe blanket



Comparison between 1-D and 3-D Tritium Breeding Results

- Compared TBR results obtained from 3-D calculations to those estimated from 1-D calculations
- The 1-D calculations are based on a toroidal cylindrical geometry model where the IB and OB blankets extend indefinitely in the vertical direction (no divertor) with a uniform neutron source extended in the vertical direction (no source peaking at mid-plane)
- 1-D estimate obtained by coupling the 1-D local TBR values with blanket coverage fractions (72.6% OB, 15.4% IB)

	Dual Coolant Flibe Blanket		Dual Coolant Flinabe Blanket	
	3-D	1-D	3-D	1-D
Outboard Region	0.8512	0.9111	0.8436	0.9104
Inboard Region	0.2193	0.2172	0.2173	0.2165
Total Overall TBR	***1.0705***	***1.1383***	***1.0609***	***1.1269***

- The combined effects of blanket and source 3-D configurations and detailed blanket heterogeneity modeling can lead to more than ~6% lower TBR compared to 1-D estimates

Nuclear Heating

	Dual Coolant Flibe Blanket		Dual Coolant Flinabe Blanket	
	3-D	1-D	3-D	1-D
Outboard Region	1.111	1.200	1.123	1.230
Inboard Region	1.256	1.300	1.269	1.330
Average	*1.136*	*1.223*	*1.148*	*1.247*

- Energy multiplication in the Flinabe blanket with thicker Be zone is slightly higher than that in the Flibe blanket
- Total nuclear heating in the IB and OB blankets is 1693 MW for Flibe and 1711 MW for Flinabe
- Energy multiplication in the IB blanket is ~13% higher than in the OB blanket since neutrons incident on the IB FW are mostly tangential resulting in more interactions in the front multiplier zone and more gamma generation in the front structure
- 1-D calculations tend to overestimate nuclear heating in the blanket by ~8% resulting in overestimating the plant thermal power

Peak FW Power Density

	Dual Coolant Flibe Blanket		Dual Coolant Flinabe Blanket	
	3-D	**1-D**	**3-D**	**1-D**
Outboard Region	*25.6*	*37.8*	*26.2*	*37.9*
Inboard Region	*20.6*	*26.5*	*21.1*	*26.7*

- The 1-D calculations result in overestimating the peak FW power density by a factor of ~1.5 in OB and ~1.3 in IB
- This is due to the approximate angular distribution of source neutrons incident on the FW from the infinitely extended uniform source in the 1-D model that results in more tangentially incident neutrons compared to the actual 3-D model with neutron source peaked at mid-plane
- This difference in angular distribution results also in a steeper radial drop in power density predicted by the 1-D calculations resulting in power density in the back wall ~8% lower than the 3-D value

FW Radiation Damage in Flibe Blanket

Peak FW damage rates at mid-plane in the Flibe blanket

	Outboard Region		Inboard Region	
	3-D	1-D	3-D	1-D
Peak dpa/FPY	*28.1*	*48.4*	*19.9*	*30.9*
Peak He appm/FPY	*356*	*625*	*243*	*384*

- The 1-D calculations overestimate the peak FW radiation damage rate by factors of ~1.7 in the OB and ~1.5 in the IB
- Again, this is primarily due to the more tangential source neutrons incident on the FW from the infinitely extended uniform source in the approximate 1-D model
- Assuming a lifetime radiation damage limit of 200 dpa for the ferritic steel structure, the blanket lifetime is expected to be ~7 FPY based on the 3-D results

Radiation Damage behind Flibe Blanket

Damage rate in the front zone of shield at different locations behind blanket

	Outboard Region		Inboard Region	
	dpa/FPY	He appm/FPY	dpa/FPY	He appm/FPY
Peak behind Manifold at Mid-plane	*0.62*	*4.53*	*1.48*	*11.85*
Poloidal Average behind Manifold	0.50	3.61	1.17	8.82
Average behind Blanket	*0.20*	*0.86*	*0.65*	*4.57*

- Peak cumulative end-of-life (30 FPY) dpa in shield structure is 45 dpa and and it is expected to be a lifetime component
- Peaking factors of 3.1 OB and 2.3 IB occur for the dpa rate and 5.3 OB and 2.6 IB for He production rate behind the manifolds
- The approximate 1-D calculations underestimate the average dpa rate at the shield by a factor of ~3 compared to 3-D calculation
- When combined with peaking factors due to the 3-D geometrical heterogeneity effects, it is concluded that 1-D calculations significantly underestimate radiation damage in the shield and vacuum vessel behind the blanket. Large design margins should be allowed when 1-D calculations are used in shielding assessment

Summary

- Detailed 3-D neutronics calculations have been performed for the dual coolant molten salt blanket designs with the low melting point Flibe or Flinabe in a tokamak power plant configuration
- The total TBR was determined to be ~1.07. Minor design modifications such as increasing the Be zone thickness enhance the TBR if needed to ensure tritium self-sufficiency
- Calculated TBR that accounts for heterogeneity and 3-D geometrical effects is ~6% lower than estimates based on 1-D calculations
- The 1-D calculations tend to overestimate nuclear heating in the blanket by ~8%
- the 1-D calculations overestimate damage and nuclear heating in the FW and front zone of the blanket by factors of 1.3-1.7
- 1-D calculations significantly underestimate radiation damage in the shield and vacuum vessel behind the blanket and large design margins should be allowed when 1-D calculations are used in shielding assessment