Fusion Blanket Design

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2020 Introduction to Fusion Energy and Plasma Physics
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ORNL, Where the Science Comes Together to Make Solutions

Nuclear science & technology

Materials science & technology

Fusion science & technology

Modeling & simulations

Pellet injection

Shattered Pellet Injection

Leadership-class computing

Whole device modeling

Material Plasma Experiment, MPEX

Materials in High Flux Isotope Reactor

Helicon 1, 2, & 3

ECH Heating

ICH Antennae

Sample location
Come Take a Look at Oak Ridge National Laboratory

Oak Ridge National Lab, America Calls
https://www.youtube.com/watch?v=xudKFiWv5OI&list=PLD37DC0FD306E52C6

ORNL, Big Impact
https://www.youtube.com/watch?v=u3W-sY9QcY0&list=PLD37DC0FD306E52C6&index=7&t=0s

High Flux Isotope Reactor
https://www.youtube.com/watch?v=RTRC1Fd_F5I

People at ORNL
https://www.youtube.com/watch?v=8yu1qrXdsh0&list=PLD37DC0FD306E52C6&index=4

Advanced Manufacturing
https://www.youtube.com/watch?v=RCkQBlFJRN4
The fusion blanket surrounds the burning plasma

ARIES-CS Blanket (stellarator)

Aubert, FED2018
What is a Fusion Blanket?

A Fusion Blanket Must: Functions

- Breed tritium
- Absorb Neutron heating
- Shield outer components
- Provide a Plasma Facing Component
- Pressure vessel (vacuum outside)
- Resist thermal and electromagnetic transients
- Contain tritium bred
- Resist failures in accident scenarios

\[
\begin{align*}
  n + ^7\text{Li} &\rightarrow ^4\text{He} + ^3\text{He} + n' \quad \text{(requires > 2.47 MeV)} \\
  n + ^6\text{Li} &\rightarrow ^4\text{He} + ^3\text{He} \quad \text{(gives 4.78 MeV)}
\end{align*}
\]
What is a Fusion Blanket?

A Fusion Blanket is Made of:

- Structural material
- Tritium breeding material
- Coolant
- Electrical or thermal insulator
- Neutron multiplier
- Corrosion coating
- Tritium permeation barriers
- Purge gas (solid breeder)
- Plasma facing material
- Plasma stabilizing materials
- Reduced activation ferritic martensitic (RAFM) steel
- Solid breeders: \( \text{Li}_4\text{SiO}_4, \text{Li}_2\text{TiO}_3, \text{Li}_2\text{ZrO}_3, \) others?
- Liquid breeders: \( \text{Pb}_{84}\text{Li}_{16}, \text{FLiNaBe (JA)}, \text{FLiBe} \)
- Helium, water, PbLi, molten salts
- Be, Be\(_{17}\)Ti, Be\(_{17}\)V, Pb (\(n \rightarrow 2n\) reactions)
- Bulk ceramics SiC, metal oxides, nitrides and carbides
- Helium, very small amount of H\(_2\) or H\(_2\)O
- Tungsten?
What is a Fusion Blanket?

A Fusion Blanket is Connected to Systems:

- Helium Cooling system → Thermal conversion system, Tritium recovery system, Fluid cleanup
- Liquid Breeder system → Thermal conversion system, Tritium recovery system, Fluid cleanup
- Helium Purge Gas system (solid breeder) → Tritium recovery system, Fluid cleanup
- Fusion Core Structural system → Blanket, structural ring, vacuum vessel, low temp shield
- Fusion Core Neutron Shielding system → Blanket, strong-back, vacuum vessel, shield
- Maintenance, Inspection, Access, Hot Cell system → Sensors, in-vessel actions, cask, cask-support systems, transfer to hot cell, hot cell breakdown
What is a Fusion Blanket?

A Fusion Blanket has many Interfaces:

- Attachment to strong back
- PF armor - first wall structure
- Liquid metal – structure
- Liquid metal – flow channel insert
- Solid breeder – structure
- Solid breeder – purge gas
- Plasma – PF armor
- Coolant – structure
- Coolant – coating
- Coolant, purge, liquid metal - manifolding

Solid breeder tritium release
1. Inter-granular diffusion
2. Grain boundary diffusion
3. Surface adsorption/desorption
4. Pore diffusion
5. Purge flow convection

Corrosion of RAFM by PbLi in a B-field

Manifolding helium into the blanket

LM manifold flow

Plasma material interactions at FW

Zinkle

Plantakis

Smolentsev

Blanchard

Youchison

Microns/year

number of samples

0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000

0 2 4 6 8 10

Microscope image of a Fusion Blanket
**US Liquid Breeder Blanket Concept**

*Miniature blanket*

- Helium flows through the small channels
- $\text{Pb}_{84}\text{Li}_{16}$ flows through the large channels

*Electric insulator for liquid metal flow in a B-field*

- EU DCLL

**Helium Cooled Blanket concept**
Japanese Solid Breeder Blanket Design

Water cooled blanket concept

Blanket module

Sector assembly

Nuclear and Thermal analysis

Most recent blanket arrangement

Tobita
Fusion Blankets Must be Replaceable

Structural and functional materials will be damaged to levels requiring they be replaced.
What is the Nuclear Environment Like for a Blanket?

Neutron energy spectra

First wall

Vacuum vessel

Magnet

Neutron Flux (n/cm²s)

Temperature: 530°C

Von Mises stress

LiPb, ~3 MPa

He, 8 MPa

plasma

plasma

H prod

He prod

Damage

He production in breeder

Tritium production in breeder

Damage [dpa/FPY] or He production [appm/FPY] or H production [appm/FPY] to FB2H

Damage in blanket

He production in blanket

Central solenoid

TF Coil

Damage in blanket

DPA

He prod

H prod
Disciplines involved in Fusion Blanket Design

- Thermo-mechanics
- Computational Fluid Dynamics
- Thermal Hydraulics
- Edge Plasma Physics
- Tritium Migration
- Liquid Metal MHD
- Materials and Manufacturing
- Transients
- Nuclear Analysis
ITER will install 4 Test Blanket Modules on ITER (mini-blankets)
Water Cooled Lead Lithium
Water Cooled Ceramic Breeder
2 Helium Cooled Ceramic Breeder

The US is a non-procuring member for the TBM program
What are Some of the Challenges We Wrestle With?

- Solid breeders or liquid breeders? Is one better than another or are they just different?
- Structural materials at high operating temperature and degradation over time
- What is the best first wall cooling/material/plasma facing approach
- Developing advanced helium cooling structures
- Corrosion of RAFM steel by Pb$_{84}$Li$_{16}$ in a magnetic field, aluminization techniques
- How do solid breeders behave when they are irradiated → Li consumption, Li migration, ceramic sintering and reconfiguration, tritium migration, etc.
- Can we really provide electrical insulation for liquid metal breeders, how does the material behave with the liquid metal and under irradiation?
- What is the tritium inventory within the fusion core, how does it move and where does it accumulate?

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Some Papers on Fusion Blankets and related

EU-DEMO Blanket: Federici et al, FED2019

JA-DEMO: Tobita et al, FST2019

CH Blanket: Songlin Liu et al, FED2019; Chenyu Xu et al, IEEE Trans Plas Sci 2018

ITER TBM: Luciano Giancarli et al, FED2018


Fusion materials and nuclear science research: Zinkle et al, FED2014

T. Ihli et al, FED2008

M. Abdou et al, FED2015