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LLNL-TR-658973-REV-1

Assessment of Tritium Breeding Blankets from a Systems Perspective - Status Report

W. R. Meier, W. R. Meier

December 11, 2014

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-TR-xxxxxx

Assessment of Tritium Breeding Blankets from a Systems Perspective – Status Report

Wayne Meier
LLNL

December 9, 2014

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences.

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1. INTRODUCTION AND EXECUTIVE SUMMARY

1.1 Introduction

The author has been engaged in the review of tritium breeding blanket (TBB) concepts for magnetic fusion energy (MFE) for the past year. The main object of the review is to provide the DOE/Fusion Energy Sciences (FES) sponsor with information to help evaluate current and near term R&D priorities with the ultimate goal of developing a TBB for future commercial fusion power plants. The approach taken in this report is to look at the TBB in an integrated system fashion and compare options against a variety of high level system objectives. This systems engineering approach does not dig into the specific details of past, ongoing or future R&D activities. This report is based on my personal review of a large body of scientific literature indicated in the bibliography and on personal communications with key R&D leaders in the field, both nationally and internationally. The views are my own, informed by the underlying research; they are not meant to represent a consensus opinion. This is a status report as of August 2014, and it focuses more heavily on liquid breeders since that is where the majority of effort has been spent. Ceramic breeders are include, but will be given more attention in the coming year. Finally, this report is intentionally written for the non-expert, beginning with an elementary description of the TBB and its functions.

1.2 Executive Summary

The goal of developing a new source of electric power based on fusion has been pursued for decades. If successful, future fusion power plants will help meet growing world-wide demand for electric power. A key feature and selling point for fusion is that its fuel supply is widely distributed globally and virtually inexhaustible. Current world-wide research on fusion energy is focused on the deuterium-tritium (DT for short) fusion reaction since it will be the easiest to achieve in terms of the conditions (e.g., temperature, density and confinement time of the DT fuel) required to produce net energy. A key component of all DT fusion power plants will be a tritium breeding blanket (TBB) that has two key functions:

1) produce more (just slightly) tritium fuel than is consumed, and
2) absorb the fusion power and make it available to a power conversion cycle (to produce electricity).

Over the past decades countless studies have examined various concepts for TBBs for both magnetic fusion energy (MFE) and inertial fusion energy (IFE). At this time, the key organizations involved are government sponsored research organizations world-wide. The near-term focus of the MFE community is on the development of TBB mock-ups to be tested on the ITER tokamak currently under construction in Caderache France. TBB concepts for IFE tend to be different from MFE primarily due to significantly different operating conditions and constraints.

This report focuses on longer-term commercial power plants where the key stakeholders include: electric utilities, plant owner and operator, manufacturer, regulators, utility customers, and in-plant subsystems including the heat transfer and conversion systems, fuel processing system, plant safety systems, and the monitoring and control systems.

In addition to meeting the two functions listed above, key stakeholder expectations include: safe operation in normal and off-normal conditions, high reliability, maintainability, high efficiency (e.g., operate at high temperature for efficiency power conversion and with low input power needs), low environmental impacts in terms of radioactive and other waste streams (over the life of the plant and after shutdown/ decommissioning).

The TBB concept is explained in more detail in the body of the report, but its essential functional features are depicted in Fig. 1.1. The primary input is power from the fusion reactions (both surface heating and nuclear heating resulting from fusion neutron reactions with blanket material). The primary outputs are thermal power and tritium. The vast majority of the blanket thermal power is removed by a blanket coolant; thus the TBB requires a coolant inlet and outlet. A small fraction of the thermal power flows to surrounding components such as the shield via low energy neutron leakage, gamma radiation and thermal radiation. Tritium is created in the TBB via nuclear reaction with lithium (see Section 2.1) and is continuously removed from the blanket. Various options for this recovery have been proposed and depend strongly on the TBB design details; in some cases T is removed with the coolant flow while other designs provide a dedicated system to capture and remove the T from the TBB. A schematic of the top level inputs and outputs of the TBB is shown in Fig. 1.2.

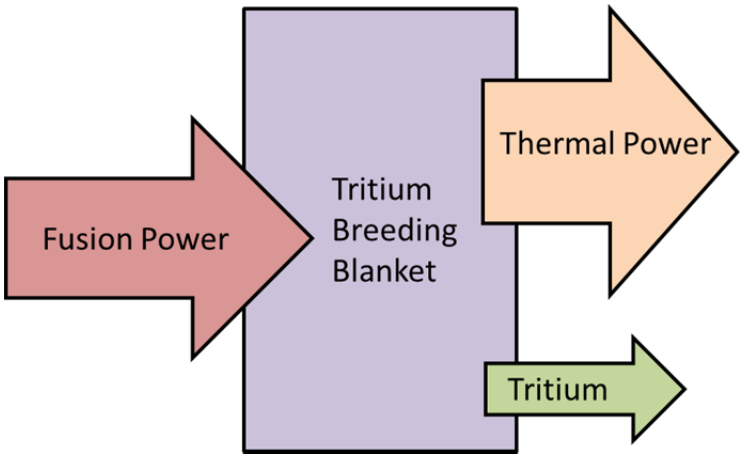

Fig. 1.1. Essential functions of the tritium breeding blanket

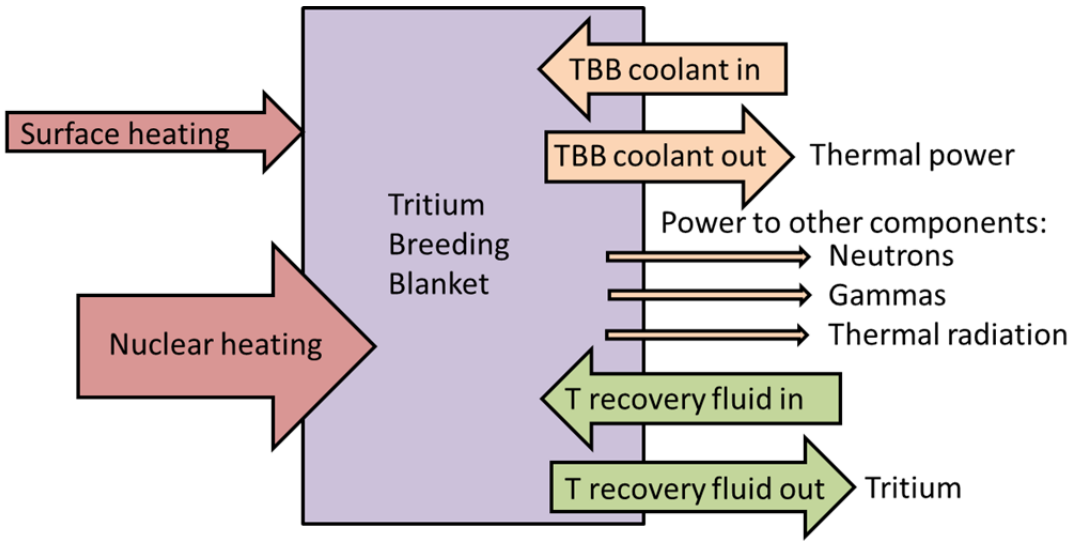

Fig. 1.2. Schematic of level inputs and outputs of the TBB.

The TBB is shown schematically in the operational context of a Tokamak power plant in Fig. 1.3. The TBB surrounds the fusion plasma and is surrounded by shielding and the magnetic coils that confine the plasma. This figure indicates the flow of DT fuel into the plasma, the D,T and He recovery from plasma exhaust (white pipe) and T extraction from the TBB (vertical green pipe not labeled). The coolant loops through the blanket provide heat to drive the turbine generator.

The scope of this report is limited to TBBs for an MFE Tokamak. World-wide there are less than a dozen designs actively being developed.

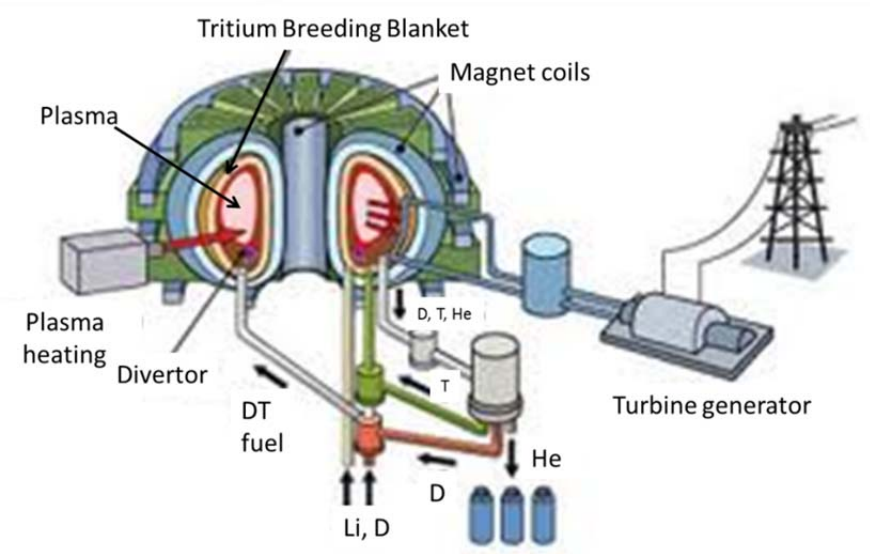

Fig. 1.3. Schematic of the power core of tokamak power plant indicating the location of the TBB (adapted from mpg.de)

2. MISSION DESCRIPTION

2.1 Introduction to the Essential Functions of the TBB

As previously noted, current world-wide research on fusion energy is focused on the deuterium-tritium (DT for short) fusion reaction since it will be the easiest to achieve in terms of the conditions (e.g., temperature, density and confinement time of the DT fuel) required needed to produce net energy. Deuterium (^{2}H or D) is a stable isotope of hydrogen with a single neutron in the nucleus (atomic mass ~ 2); it occurs naturally and can be extracted from water. Tritium (^{3}H, or T) is also an isotope of hydrogen with two neutrons in the nucleus giving it an atomic mass of ~3. Tritium is radioactive, decaying by beta emission (which transforms this hydrogen isotope into a helium isotope, denoted ^{3}He) with a half-life of 12.3 years. Due to this relatively short half-life, there is no natural abundance of T. Therefore, fusion power plants based on the DT reaction must produce their own T. The process is referred to as tritium breeding, and the component of the fusion power plant that carries out this function is called the tritium breeding blanket (TBB), or breeding blanket, or simply blanket.

To understand how it is possible for a power plant to create its own fuel, we need to look at the nuclear reactions involved. The DT fusion reaction is

$$D + T \rightarrow {}^4He + n + \text{energy released.}$$

The nuclear reaction between D and T produces a helium nucleus (also called an alpha particle, α) and a neutron. In the process energy is released that appears in the form of kinetic energy of the alpha particle and neutron. To create tritium to provide a continuous supply of fuel, the neutron must initiate nuclear reactions with lithium (an alkali metal that is abundantly available in the earth's crust). Lithium has two isotopes, ^{6}Li and ^{7}Li and both have T producing reactions with neutrons emitted by the fusion reaction:

$$^6Li + n \rightarrow T + \alpha \text{ and}$$

$$^7Li + n \rightarrow T + \alpha + n'$$

Both reactions produce a new T and a helium nucleus. The reaction with ^{7}Li also emits another lower energy neutron (n') that can subsequently produce more reactions with ^{6}Li. In this way, one fusion neutron can result in more than one T reaction product.

The TBB must produce at least as much T as is consumed in the fusion reactions.

The ratio of T atoms produced in the blanket to T atoms consumed in the fusion reactions is called the tritium breeding ratio, TBR. Breeding blanket designs typically have a goal of breeding an extra10% (TBR = 1.10) to account for uncertainties in the predicted blanket performance, supply T start-up inventory for new power plants, account for radioactive decay,

and account for losses in the fuel processing systems (losses to the environment must be extremely low).

To accomplish the requirement of obtaining a TBR greater than 1.1, the TBB must completely surround the fusion power source, with the exception of areas required for plasma heating, vacuum pumping, and in the case of IFE, beam port entry. As a result, the TBB absorbs nearly all the fusion power and this power must be made available to a heat transfer system that transports thermal power to a power conversion system to produce electricity. This power flow is shown schematically in Fig. 1.3.

While it is possible to achieve a TBR>1.1with a liquid Li blanket (just based on the extra neutrons from the 7Li reaction), most TBBs also include a neutron multiplier material. Beryllium (Be) or Be compounds are commonly use, particularly for TBB based on Li ceramics. Lead (Pb) is also an effective neutron multiplier and is present in TBB designs using a lithium-lead molten metal coolant. Both these elements undergo (n,2n) reactions thus multiplying the number of neutrons available that can subsequently be captured in T breeding reactions primarily with ^{6}Li, which has a high cross section for low energy neutrons.

The fusion power is delivered to the TBB as both surface heating and penetrating nuclear heating. The structure that is directly exposed to the fusion source is called the first wall and is considered an integral part of the TBB. It must absorb and conduct the surface heat to the blanket coolant. Fusion neutrons penetrate into the blanket and cause heating due to nuclear reactions with blanket materials (nuclear heating), the most important of which are the tritium breeding reactions with lithium. In order for the plant to produce electric power, the blanket thermal power must be removed at a temperature that is high enough to drive the selected power conversion cycle. Designs being considered typically operate with blanket coolant outlet temperature greater than 400 C.

The TBB must absorb the fusion power and make it available to the power conversion systems at high temperature.

2.2 Active Stakeholders

This section covers the active stakeholders. In this report we take the context as the future where fusion power has been proven feasible and it has become an option for a commercial electric power plant. The most important current stakeholders are the agencies currently sponsoring R&D on TBBs (e.g., DOE), but their plans must ultimately be focused on developing a product for commercial use. Thus the criteria should be similar if not the same.

2.2.1 Utility Owner/Operator

We assume that it is the electric utility that makes the decision to build and operate the fusion power plant as part of its energy supply mix. This is clearly a key stakeholder since without a

positive decision on their part the plant, including the TBB, is not built. Top level expectations of the utility owner/operator include the ability to produce and sell electricity in an economically competitive, reliable, safe and environmentally acceptable manner. In order to meet these top-level expectations, the TBB is expected to:

- Supply the tritium fuel
- Have an acceptable capital cost (as part of the overall plant capital cost)
- Have an acceptable operating cost (fixed and variable)
- Facilitate high efficiency power conversion
- Have high availability
  - Reliability (low unplanned outages)
  - Maintainability (short maintenance times)
- Operate safely in normal and off-normal conditions including (start-up and shut-down)
- Have low radioactive and hazardous waste streams (during plant operations and at end of plant life).

2.2.2 Plant Maintenance Personnel and Equipment

During the life of the power plant, the TBB will certainly require repair and/or replacement. Neutrons from the fusion reaction will cause blanket materials to become radioactive over time to the point that hands-on maintenance will not be possible. Therefore, the TBB must be designed to allow access and repair by remote maintenance equipment. Ideally the expectations would include easy access for either in situ repair or rapid removal and replacement with new or refurbished blanket components.

2.2.3 Fusion Plasma

As previously noted the TBB nearly completely surrounds the fusion plasma with the exception of ports needed for heating, vacuum pumping, plasma fueling and exhaust at the divertor. As such, the geometry of the TBB must conform to the geometry of the plasma which is set by the magnetic configuration. The inner surface of the TBB is called the first wall and it is directly exposed to the fusion plasma. Plasma interactions with the first wall can cause first wall material to be expelled into the plasma core. Expectations here are that the TBB blanket can be designed to conform to the plasma geometry and that the first wall design and operating conditions do not prevent the plasma from behaving as expected.

2.2.4 Heat Transfer System

The heat transfer system also interacts directly with the TBB. Some means must be provided to extract the fusion power that is deposited in the blanket and deliver the power to a power conversion system. Various liquid and gas coolants are being considered. The heat transfer fluid is delivered through an inlet connection (typically a pipe), flows through the blanket as it is heated and then exits through an exit connection. The expectation is that the TBB can be

designed to allow enough heat transfer area between the blanket structure and the coolant to allow for efficient heat transfer under reasonable coolant flow conditions (e.g., pressure, flow velocity, temperature change from inlet to outlet).

2.2.5 Tritium Processing System

Tritium that is bred in the blanket must be continuously removed and delivered to the tritium processing system (TPS). Various approaches have been considered and deemed feasible. In some cases the T is removed as a part of the coolant flow stream, while other designs provide a dedicated method for T extraction, for example a flow stream of He that picks up T as it flows through the breeder material. The expectation is that the TBB can be designed to allow for continuous T removal in a manner that does not require excessive electrical power and does not allow a large inventory of T to build up in the blanket. Excessive power consumption would reduce the amount of electricity available for sale and thus adversely impact the plant economics. High T inventory in the blanket is a safety issue for the power plant.

2.2.6 Instrumentation and Controls (I&C) System

Thermal and mechanical aspects of the TBB will be monitored to assuring that it is operating within allowable ranges. The expectation is that the design of the TBB will accommodate monitoring sensors needed to determine and, if need be, adjust plant operating parameters related to the TBB functions, e.g., adjusting the coolant flow rate.

2.2.7 Plant Safety Systems

Various accident scenarios will be evaluated for the power plant including accidents that could involve the TBB, e.g., loss of coolant flow to the blanket, loss of T containment, etc. The specific types of possible accidents and safety systems needed to mitigate consequences will depend on the TBB design details. Expectations are that the TBB will be designed to operate safely in normal and off-normal conditions including accommodating possible active measures in response to an accident, e.g. supplemental cooling, drain tanks, fire suppression, etc.

2.3 Passive Stakeholders

This section describes those stakeholders that indirectly influence the TBB.

2.3.1 Manufacturer/Supplier

It is likely that the TBB components will be manufactured by an industrial supplier that will contract with the plant owner to build and deliver components to the plant site. Expectations of the manufacturer/ supplier are that the TBB can be built at a cost that is acceptable to the owner. Considerations include design complexity, cost and availability of materials, industrial experience with required manufacturing techniques, ability to meet industrial standards, e.g., AMSE.

2.3.2 Builder/Installer

The TBB is too large to assemble in a factory and deliver as a single unit to the power plant; it will be delivered as a large number of components. The plant owner will contract with an Architect-Engineering firm to build the plant, including installation of the TBB. The builder/installer expects that the TBB design can be assembled and installed in a straightforward manner and not lead to delays in the construction schedule. Considerations include component complexity, weight, number of on-site connections to other components, interfaces to coolant and T recovery systems.

2.3.3 Regulators

The plant owner will need to secure a license to operate from regulators, which could include local, state and federal requirements. With respect to the TBB, the most important regulations will relate to plant safety. Expectations are safe operation in normal and off-normal conditions especially containment of T and preventing release of radioactive or chemically hazardous materials to the surrounding environments.

2.3.4 Utility Customers

Utility customers are passive stakeholders in that they receive the electricity generated by the plant. Their expectation is for reliable delivery of electricity at an affordable price. A plant with high availability is needed to meet these expectations. The TBB must be highly reliable so as not to adversely impact overall plant availability. Also its capital and operating costs cannot be excessively high.

2.3.5 Plant Personnel (other than maintenance)

The power plant will have hundreds of employees to operate and maintain the plant. Most will have no direct interaction with the TBB but expect a safe working environment. The TBB must be designed for safe operation in normal and off-normal conditions.

2.3.6 Neighboring Public

The public in areas surrounding the power plant also expect that the plant will not endanger their safety or health. The TBB must be designed for safe operation in normal and off-normal conditions.

2.3.7 Surrounding Ecosystem

The fusion plant is expected to operate in a manner that does not have significant environmental impacts and this will be carefully reviewed and studied as part of the licensing process. The expectation is that the TBB subsystem of the plant will not lead to adverse environmental impacts.

2.4 Essential Performance Criteria

From the above, we conclude that the essential performance criteria are that the TBB:

1) Produce more T fuel than is consumed and allow for continuous recovery,
2) Absorb fusion power and make it available to the power conversion system at high temperature,
3) Operate safely in normal and off-normal conditions.

3. SYSTEM OPERATIONAL CONTEXT AND REFERENCE OPERATIONAL ARCHITECTURE

3.1 System Operational Context

The operational context for the TBB considered in this report is a future commercial MFE power plant. The functional boundary of the system is shown in Fig. 3.1 (the same as Fig. 1.2). A context diagram for the TBB showing active and passive stakeholders is given in Fig. 3.2.

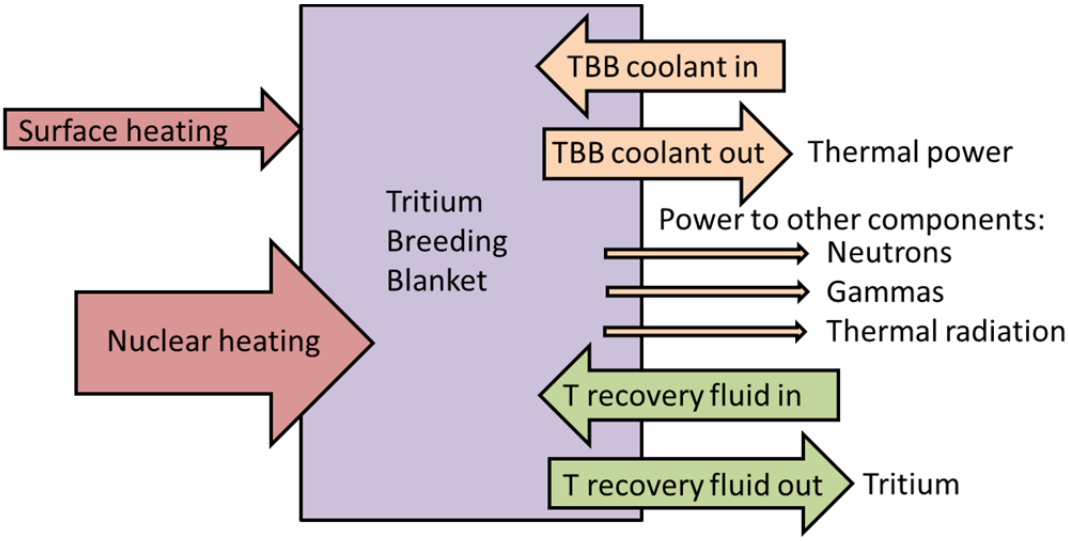

Fig. 3.1 Function boundary of the TBB showing primary inputs and outputs.

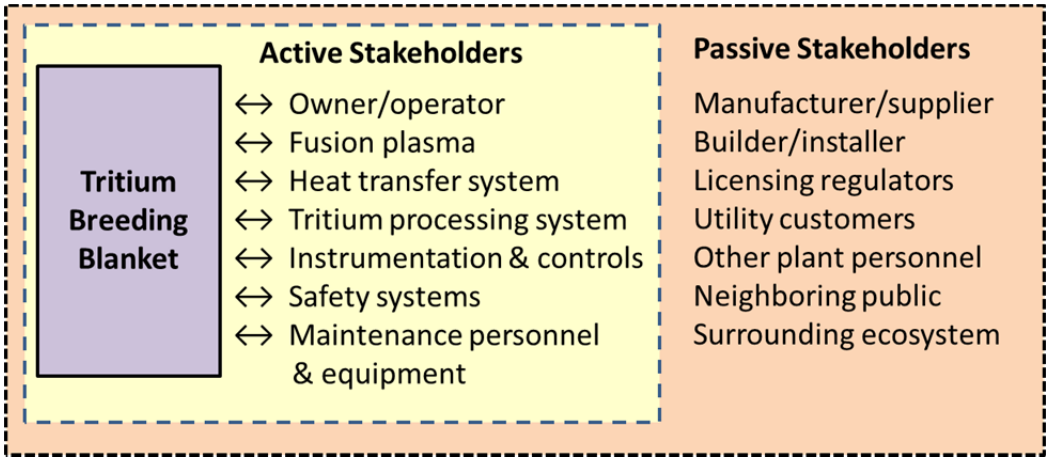

Fig. 3.2 Context diagram indicating Active and Passive Stakeholders.

3.2 Reference Operational Architecture

Since commercial fusion power is a couple decades off, there are many TBB concepts under development worldwide. While there is not yet a clear *reference architecture*, we take the helium cooled, lithium-lead (HCLL) TBB concept as the starting point for the purposes of this report. This concept is currently favored in the EU and is a candidate TBB for several other countries with strong fusion development programs (i.e., ITER partners). The US, however, has proposed a modified version of the HCLL that has improved thermal efficiency potential; this concept will be considered as one of the alternates evaluated later in the report.

3.2.1 Helium Cooled Li-Pb TBB

The HCLL blanket concept is illustrated schematically in Fig. 3.3. The essential features are the TBB module structure; He coolant inlet, distribution and outlet; LiPb supply, distribution and outlet. A steel containment structure defines the shape of the TBB module including the first wall (FW) that faces the plasma. The entire blanket that surrounds the fusion plasma will be made up of hundreds of these modules. Helium coolant inlet/outlet pipes are attached to the structure as are LiPb inlets and outlets. The internal features of the TBB module are designed to distribute the LiPb and He in a manner that the tritium breeding and cooling functions are achieved. Figure 3.4 is a more realistic illustration of how the TBB module would look.

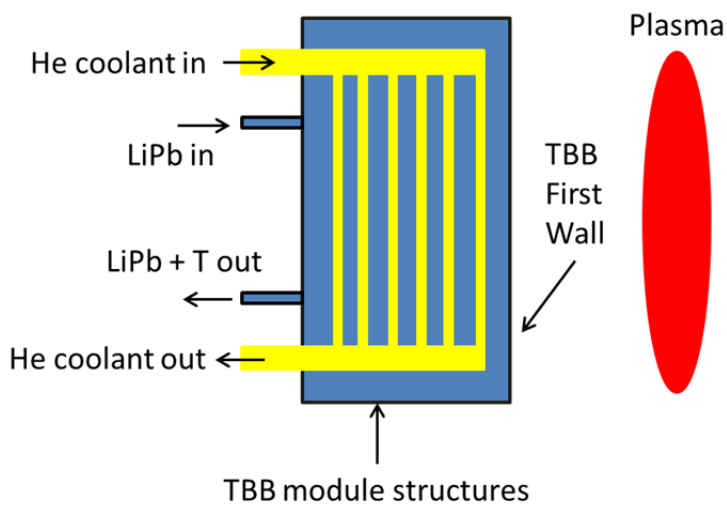

Fig. 3.3 Schematic of the HCLL TBB module.

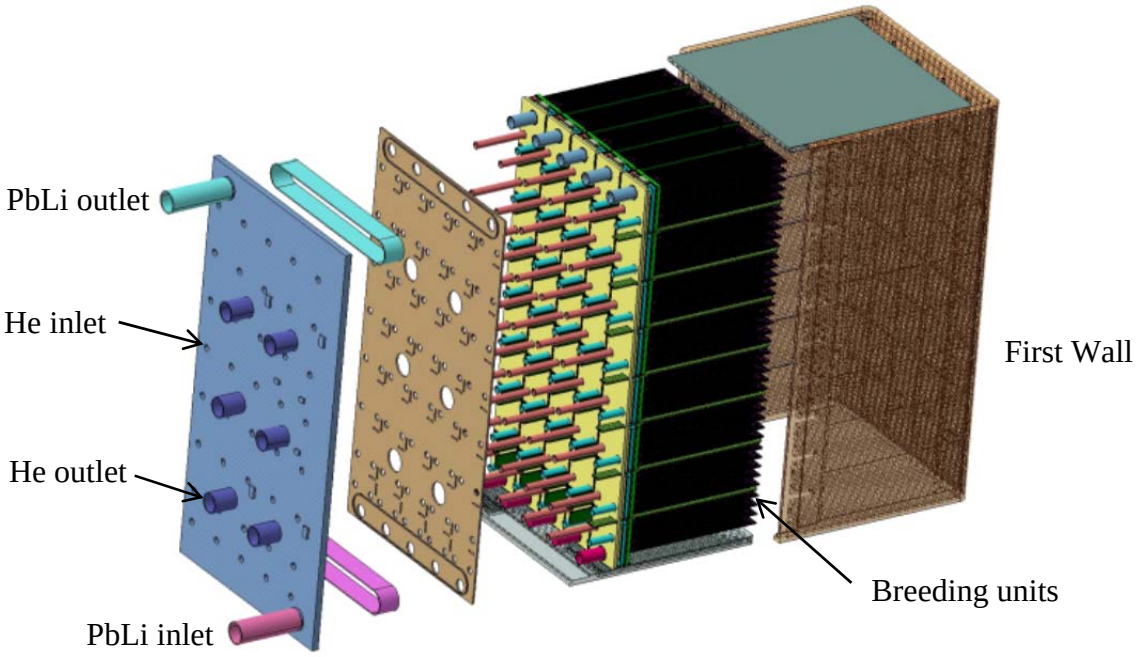

Fig. 3.4. More detail concept illustration of the PbLi TBB module (from L.V. Boccaccini et al, "Design and Development of DEMO Blanket Concepts in Europe," IAEA Demo workshop, 2012)

4. SYSTEM DRIVERS AND CONSTRAINTS

The system drivers for the TBB design evolve from the essential performance criteria listed in Section 2.4.

Tritium Breeding Performance. The materials used in the TBB and their configuration must be such that a TBR> 1 can be achieved. This sets constraints on the type of materials that can be used (e.g., strong neutron absorber must be avoided), the relative fractions of materials (i.e., need sufficient atomic density of Li), the arrangement of materials within the TBB (e.g., neutron multipliers if used must be placed toward the plasma side of the TBB to be effective), and the overall thickness of the TBB (since fusion neutrons are very penetrating). A wide variety of TBB design concepts have been proposed that meet these constraints.

Power Recovery and Conversion Performance. The requirement for absorbing the fusion power and making it available to the power conversion system at high temperature is also a significant design driver. The design must incorporate a method for heat removal, typically accomplished by either flowing a liquid metal breeder (such as Li, PbLi or molten salt) or by incorporating coolant flow channels through the TBB. This cooling function must be achieved while not preventing the essential T breeding function. Constraints include considerations of compatibility of coolants with structural materials they contact at the temperatures needed for efficient power conversion (i.e., minimizing corrosion), possible magneto-hydrodynamics (MHD) power losses due to flowing liquid metals in the Tokamak's magnetic fields, and the need to avoid contamination of the coolant by T if the breeder is not also the coolant. The ability to operate at high temperature is a strong economic driver for the plant since the power conversion efficiency increase with coolant temperature. The pumping power to circulate the coolant, particularly He, reduces the net electric power available and thus net plant efficiency.

Safe Operation. Safety is a significant design driver and impacts the selection of TBB structural materials (low activation materials are preferred or even required) and also the breeder itself (low chemical activity is preferred). The licensing and regulatory review will require integrated safety analyses of possible accident scenarios for the plant. Failure of the TBB and release of T or other radioactive material can impact those results. As such, constraints may arise from the safety but they are very design depend and cannot be generalized (e.g., limits on the amount of Li in the TBB).

5. PREFERRED CONCEPT SELECTION AND RATIONALE

In this section we describe alternative for the key system elements that make up the TBB and give the rationale for selecting a preferred TBB design.

5.1 TBB Components Options

The following tables highlight some key feature of the major constituents of possible TBB designs: Table 5.1 covers tritium breeders, Table 5.2 neutron multipliers, Table 5.3 coolants, and Table 5.4 structural materials.

Table 5.1 Tritium Breeder Options.

Tritium Breeder	Key Properties	Features/Advantages	Issues
Li	Liquid metal, T_{melt} = 181C	• High TBR potential • Dual function, also used as coolant • Good heat transfer properties • Low melting point • Neutron multiplier not needed • Affinity for T, low permeation losses	• Chemically reactive, burns with air and water, safety issue • T recovery more difficult due to being tightly bound to Li • Liquid metal corrosion of structures
PbLi	Liquid metal, T_{melt} = 235C	• Good TBR potential • Dual function, also used as coolant • Good heat transfer material • Acceptable melting point • Pb serves as neutron multiplier • Less reactive than Li (safer) • Low T solubility, ease of T recovery	• High density leads to high mass TBB, structural implications • Special measures need to limit T permeation losses • Liquid metal corrosion
Flibe	Molten salt, T_{melt} = 300C	• Marginal TBR • Dual function, also used as coolant • Good heat transport capability • Be serves as neutron multiplier • Better safety than Li • Ease of T recovery (like PbLi)	• Expensive • Low heat transfer coefficient • Special measures need to limit T permeation losses • Corrosion
Ceramics (e.g., Li_4SiO_4, Li_2TiO_3, etc.)	Ceramic pebbles	• Acceptable TBR • Compatible with most structural materials • High temperature operation, high efficiency possible.	• Requires neutron multiplier • Radiation damage may impact ease of T recovery • Requires separate He purge loop for T recovery

Table 5.2 Neutron Multiplier Options

Neutron Multipliers	Key Properties	Features/Advantages	Issues
Be	Metal typically in pebble form	• Very good neutron multiplier	• Expensive • Resource limited • Handling care needed
Pb	Liquid metal T_{melt} = 328C	• Good multiplier	• Produces activation product Po
Pb as part of PbLi	Liquid metal	• Can serve functions of breeding, coolant and tritium removal	• Produces activation product Po
$Be_{12}Ti$	Intermetallic	• Almost as good at Be, higher operating temp	• Expensive • Resource limited • Handling care needed

Table 5.3 Coolants Options.

Coolants	Key Properties	Features/Advantages	Issues
Li	Liquid metal, T_{melt} = 181C	• Excellent HT coefficient • Low mass density • Dual function, also breeder	• Safety • Chemical reactivity • MHD losses
PbLi	Liquid metal, T_{melt} = 235C	• Good HT coefficient • Dual function, also breeder	• High mass density • MHD losses
Flibe	Molten salt, T_{melt} = 300C	• Adequate • Dual function, also breeder	• Poor convective HT
He	Gas used at high pressure (~8 MPa)	• Inert, no corrosion issues • High temperature capability • High efficiency power cycles	• High pressure operation • High pumping power
Water	Liquid at room temperature	• Proven technology • Lower cost option • Good heat transfer and heat transport properties • No MHD issues	• Thermal cycle efficiency lower than liquid metal or He cooled designs • Reactivity with Li and PbLi

Table 5.4 Structural Material Options.

Structural Materials	Features/Advantages	Issues
Stainless Steel	• Readily available	• High activation if Ni included
Ferritic Martensitic Steel (FMS)	• Available • Low activation	• DTBT limits operating temperature window • Limited radiation damage life (total displacement per atom)
Oxide Dispersion Strengthened Steel (ODS)	• Low activation • Longer radiation damage life than FMS • Higher strength than FMS	• Needs more R&D • Not yet available in large quantities
Vanadium	• Compatible with Li • Low activation	• Expensive • Difficult to fabricate

5.2 Example TBB Component Combinations

There have been a number of TBB conceptual designs proposed using various combinations of breeder, neutron multiplier, coolant and structural material. The following seven include the commonly considered combinations, although other options are possible. In all cases, the PbLi is in liquid state, even if it is not used as the coolant (i.e., cases 2 and 3); this is necessary to allow continuous tritium recovery.

Name (abbreviation): Breeder / Multiplier / Coolant / Structure

1. Lithium/Vanadium (LV): Li / none / Li / V
2. Water Cooled Lead Lithium (WCLL): PbLi / Pb in PbLi / water / FMS
3. He Cooled Lead Lithium (HCLL): PbLi / Pb in PbLi / He / FMS
4. Dual Cooled Lead Lithium (DCLL): PbLi / Pb in PbLi / PbLi and He / FMS
5. DCLL with FCI (DCLL-FCI): PbLi / Pb in PbLi / PbLi and He / FMS with FCI
6. Molten Salt (MS): Flibe / Be in Flibe / Flibe / ODS
7. He Cooled Pebble Bed (HCPB): Ceramic Breeder / Be / He / FMS

5.2.1 Comparison with Respect to Stakeholders Expectations

In this section we compare the concepts based on how well they meet stakeholder expectations and system requirements. The expectations are weighted and an overall ranking of the concepts is then determined.

The top level expectations/requirements are:

1. Tritium Supply (TS): Produces more T fuel than is consumed in a manner that allows for continuous recovery. Ease of obtaining a TBR > 1 is desirable.
2. Power Handling (POW): Absorbs fusion power and makes it available to the power conversion system at high temperature. Low coolant pumping power is desirable.
3. Safety (SAF): Operates safely in normal and off-normal conditions.
4. Costs (COST): Has acceptable capital and operating costs.
5. Reliability (REL): Operates with high reliability leading to high availability.
6. Environmental (ENV): Has low environmental impact from radioactive waste.
7. Tritium extraction (TEX): Ease of tritium recovery from the breeder is favored.
8. Fabricability (FAB): Can be fabricated with standard, proven methods.

Table 5.5 scores the concepts relative to the DCLL blanket using the following scale.

Ability/ease of meeting the given expectation/requirement compared to the DCLL is:

1. Much lower / much harder
2. Moderately lower / moderately harder
3. Roughly comparable
4. Moderately better / moderately easier
5. Much better / much easier.

Table 5.5 Comparison of concepts on ability to meet key expectations relative to the DCLL.

Expectation →	**1 TS**	**2 POW**	**3 SAF**	**4 COST**	**5 REL**	**6 ENV**	**7 TEX**	**8 FAB**
Concept								
LV	4	4	1	1	3	4	2	1
WCLL	1	1	2	4	4	3	3	4
HCLL	3	2	2	2	2	3	3	2
DCLL	3	3	3	3	3	3	3	3
DCLL-FCI	3	4	3	2	3	3	3	2
MS	2	3	3	3	3	4	3	1
HCPB	2	4	4	2	2	4	2	2

The results of this top level comparison are summarized as follows:

- The LV concept has advantages in terms of good T breeding performance, power extraction (good heat transfer and low pumping power) and environmental criteria (since Li does not activate). It suffers for safety concern with the use of Li, the difficulty of extracting T from Li and the use of an expensive structural material (V) that is difficult to fabricate.
- The WCLL main advantage is a power cycle based on proven technology leading to lower cost and likely higher reliability for the overall system. It disadvantages are limited operating temperature giving a lower conversion efficiency than the others and concerns over the possibility of accidental interaction of water and PbLi.
- The HCLL concept gets solid ratings across the board with the exception of power extraction. Relying on He to recover all the blanket power requires significant coolant pumping power and impact overall conversion efficiency.
- The DCLL overall is an attractive concept meeting all expectations. As the point of comparison all scores are 3.
- The DCLL-FCI has power conversion advantages since higher outlet temperatures and thus higher efficiency can be obtained. The addition of the FCI adds cost and fabrication complexity.
- The MS concept has several negatives related to its poor convective heat transfer coefficient, high cost of the molten salt and fabricability using the more advanced ODS steel.
- The HCPB is a solid performer across the board, but like the HCLL, will have higher coolant pumping power impacting the plant's net efficiency.

Weighting the expectations is somewhat subjective and depends on the stakeholder. Taking the view of the utility owner/operator led to the following weightings. Since it is difficult to rank the importance of eight criteria, I used the pair-wise comparison technique of the Analytic Hierarchy Process, AHP (see App. C) to develop these weightings.

Table 5.6 Weighting for the Comparison Criteria.

Criteria	**Weight**
Tritium Supply (TS)	0.273
Power Handling (POW)	0.166
Safety (SAF)	0.197
Costs (COST)	0.034
Reliability (REL)	0.116
Environmental (ENV)	0.095
Tritium Extraction (TEX)	0.075
Fabricability (FAB)	0.044

Applying the weights in Table 5.5 to the rankings in Table 5.6 and summing, gives the overall score for each concept. The normalized results in given in Table 5.7

Table 5.7 Overall score for the blanket concepts listed in rank order.

Concept	Weight
DCLL-FCI	0.161
DCLL	0.156
HCPB	0.152
LV	0.151
MS	0.142
HCLL	0.127
WCLL	0.110

Based on this evaluation, the DCLL-FCI concept is rated the highest, but the margin over the reference case DCLL is not dramatic (~3%). The HCPB and LV concept scores are comparable and less than 7% lower than the DCLL-FCI. The MS, HCLL and WCLL concepts are lower still, with the WCLL significantly so. These results point to the fact that every concept has its pluses and minus, and when scored for the different comparison criteria, the results tend to flatten out; there is no clear “winner.” As a result, it is prudent to continue R&D on portfolio of TBB concepts and not focus on just one.

6. PROPOSED SYSTEM ARCHITECTURE

6.1 Recommended Configuration

Based on the previous comparison, the recommended configuration is the DCLL with flow channel inserts (FCI). Key features of this TBB configuration are illustrated in Figs. 6.1 and 6.2. The schematic in Fig. 6.1 illustrate how the FCI is positioned between the flowing PbLi breeder and the steel structures of the TBB which are cooled with high pressure He. The FCI insulates the steel so that the outlet temperature of the PbLi coolant can exceed the limiting operating temperature of the steel. Figure 6.2 gives a more realistic view of the TBB configuration. This figure illustrates the routing of the He and PbLi coolants. It also shows how all regions that are filled with PbLi are lined with SiC.

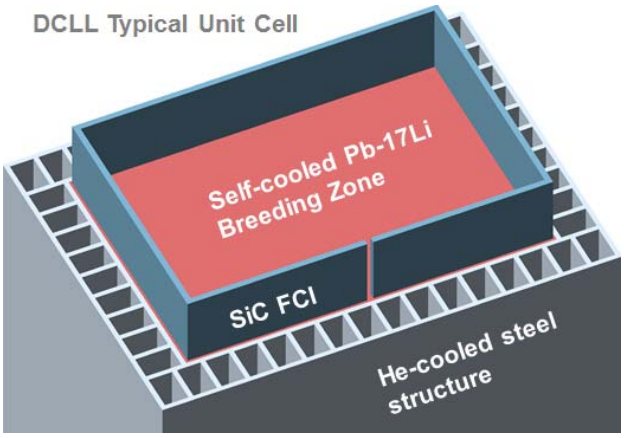

Fig. 6.1 Schematic of DCLL configuration showing how the SiC flow channel insert is positioned in the PbLi coolant/breeding region (from N. Morley, FPA meeting, 10/11/2005)

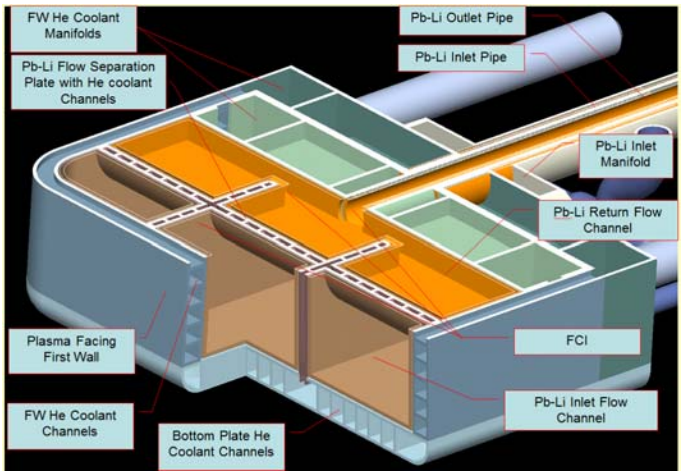

Fig. 6.2. A more detailed diagram showing the internal configuration of the DCLL TBB using FCI (from N. Morley, FPA meeting, 10/11/2005).

6.2 Comparison of Processes

The original DCLL TBB design and the selected DCLL-FCI design operate in virtually the same manner with a two key differences:

1) The DCLL-FCI can achieve a higher PbLi outlet temperature which leads to a more efficient thermal conversion systems and better overall plant economics. This is due to the thermal insulating effects of the FCI.
2) The electrical insulating properties of the FCI reduce the MHD pressure drop and overall pumping power for the PbLi coolant. This translates into less recirculating power and higher net plant efficiency. Alternatively, a higher flow rate for the same MHD loss may have some advantage in terms of maintaining a lower T inventory in the PbLi by virtue of more rapid processing for T recovery.

Beyond these two factors, the concepts are comparable.

7. SYSTEM REQUIREMENTS

7.1 List of System Requirements

The system requirements for the DCLL design are listed here.

1. The tritium breeding material shall be the eutectic of PbLi with 15.7 atomic percent Li.
2. The PbLi shall be molten to allow flow through the TBB.
3. The inlet temperature of the PbLi shall be at least 50 C above the melting point.
4. The outlet temperature of the PbLi shall be 600C or more.
5. All PbLi flow channels shall be lined with SiC flow channel inserts.
6. The FCI material shall be constructed in a manner to provide thermal insulation between the PbLi and steel structures.
7. The FCI shall be constructed to provide magnetic isolation between the flowing PbLi and the steel channel walls.
8. The TBB structure shall be the ferritic/martensitic steel, such as F82H.
9. The maximum steel temperature shall be 550C.
10. The coolant for the TBB structures shall be helium at ~8 MPa pressure.
11. The helium coolant channels shall be configured to keep the He pumping power as low as possible, ideally below 10% of the plant gross electrical power.
12. The TBB shall accommodate sensors for temperature, pressure and strain.
13. The PbLi inlet/outlet flow connects shall allow for gravity draining.

7.2 Mapping of Systems Requirements to Expectations

Table 7.1 shows a mapping of the system requirements to the same list of stakeholder expectations discussed in Section 5. This is done to show that the system requirements are indeed required.

Table 7.1 Mapping Systems Requirement to Key Expectations

Expectation* →	**1 TS**	**2 POW**	**3 COST**	**4 SAF**	**5 REL**	**6 ENV**	**7 TEX**	**8 FAB**
System Requirement								
1. Use PbLi	X	X		X			X	
2. Molten	X	X					X	
3. T inlet				X	X			
4. T outlet		X		X	X			
5. Use FCI		X		X				
6. Thermal insulation		X						X
7. Magnetic insolation		X						X
8. F82H Steel			X			X		X
9. Steel max temp.				X	X			
10. He Coolant		X		X				
11. He pump power		X	X					
12. Sensors		X		X	X			
13. Gravity drain				X	X			

*See Table 5.5 for list of Expectations

The rationale for the mapping of system requirements (SR) against stakeholder expectations is briefly summarized here.

SR1: PbLi is an effective tritium breeding material. It is used for power extraction and is safer than the alternative liquid lithium. Tritium extraction via vacuum permeation is feasible.

SR2: PbLi must be molten in order to perform the cooling function and allow for continuous T extraction. It also allows online replenishment of Li that is depleted in the T breeding process, thus impacting the tritium supply expectation.

SR3: Inlet temperature must be high enough to avoid the possibility of freezing and plugging a coolant channel, which could impact the safety and reliability of operations.

SR4: Outlet temperature determines the thermal cycle efficiency thus impacting power extraction expectation. If it is too high, the structural materials could exceed safe and reliable limits.

SR5: Use of the FCI has a major impact on the upper limit on operating temperature. It impacts the safety expectation indirectly in that it allows for more rapid PbLi flow and thus enables T extraction to lower levels.

SR6: Thermal insulation allows high outlet temperature and efficiency. Also allows the use of available FM steel

SR7: FCI magnetic isolation reduces MHD losses and lowers pumping power.

SR8: F82H is likely lower cost and easier to fabrication than more advanced steels. Its low activation characteristics impact safety.

SR9: The maximum steel temperature is set by strength and corrosion consideration, thus related to safety and reliability.

SR10: He coolant is used for power extraction. Operating at a high pressure allows for more efficient heat removal.

SR11: The limit on He coolant pumping power impacts the TBB He coolant channel configuration for power extraction. The impact of He pumping power on the net electric power for sale can be viewed as an operating cost.

SR12: Sensors for monitoring TBB conditions are needed to assure power extraction, detect off-normal conditions with potential safety impacts and assure operating conditions do not overly stress the system which could lead to early failure and reduced reliability.

SR13: The requirement for gravity drain of the PbLi coolant is needed for off-normal shutdown and will also make normal servicing easier.

8. RISKS AND TECHNOLOGY ASSESSMENT

8.1 Risk Assessment

Here we compare the risk of not meeting essential performance criterial (EPC) for the original DCLL TBB and the DCLL-FCI TBB.

EPC1) Produce more T fuel than is consumed and allow for continuous recovery

There is high confidence that both concepts can meet the tritium breeding requirement due to the use of the same breeding materials which has enough margin (TBR > 1.1) to present little risk. The DCLL-FCI has additional material that could have a slight negative impact on the TBR, but the use of SiC minimizes this impact.

EPC2) Absorb fusion power and make it available to the power conversion system at high temperature

Both concepts provide viable methods of extracting the fusion power and delivering it to the power conversion system. The risk of not meeting this expectation is low. As previously noted, the selected concept with a FCI can achieve high PbLi outlet temperatures and thus improve the thermal efficiency for the plant. To take advantage of the higher outlet temperature, more advance power conversion systems must be employed which carry a degree of additional development risk. This is significantly mitigated by the fact that the international power industry is already developing advanced, high temperature systems for other energy systems such as nuclear, coal and natural gas.

EPC3) Have acceptable capital and operating costs

There is significant uncertainty and risk associated with the economics of future fusion power plants, but these are not strongly coupled to the TBB. The addition of FCI should not have a significant impact on the total capital cost of the power plant since the blanket is a small part of the overall system. The fact the DCLL-FCI allows for a higher flow rate and minimizes conduction of the breeder heat into the He coolant stream means that there is less power removed by the He coolant. This is an advantage due to the potentially high pumping power demands of the He cooling. Further R&D is needed to see if lower He pressure and therefore thinner structures can be used with the FCI enhance design.

EPC4) Operate safely in normal and off-normal conditions

With proper overall design, there is confidence that the plant will meet safety expectations. Tritium management (total inventory, losses, accidental leaks, etc.) is extremely important in this regard. The DCLL-FCI may have somewhat lower risk if the higher allowable flow velocity translates to a lower steady state T concentration in the PbLi. Continued R&D on efficient T extraction processes are needed for both designs.

9. KEY FINDINGS AND RECOMMENDATIONS

9.1 Findings

The overall systems level comparison of TBB concepts supports the U.S. R&D community's decision to focus on the Dual Coolant Lithium Lead design with Flow Channel Inserts (DCLL-FCI) as the top candidate. It is one of several concepts that have a good chance of meeting all the system requirements, and it has some potential advantages, although not dramatic, over competing concepts in terms of its eventual performance.

9.2 Recommendations

All concepts are in early stages of development, and component level testing in a fusion relevant environment will not take place until the Test Blanket Modules are deployed in ITER. Therefore, it is prudent to 1) continue along the current path of also conducting R&D on a solid breeder blanket concept, and 2) devote some portion of the R&D effort to less developed, innovative ideas that have the potential for addressing key issues with the mainline approaches or improving predicted performance. Most Major fusion programs, including the EU, Japan, Korea and China, recognize the risk of down selecting to a single concept at this stage; they are all conducting R&D on different breeders (liquid and solid) and coolants (water, gas and liquid metal). Even with limited funding it is recommended that the U.S. strive to do the same.

Appendix A

Tritium Breeding Blanket Data Sheets

Korean Helium Cooled Ceramic Reflector (HCCR)

Proponent: South Korea

Breeding Material: Li_4SiO_4 pebble bed (Li_2TiO_3 alternate)

Multiplier: Be pebble bed

Reflector: Graphite pebble bed (SiC coated)

Coolant: Helium at 8 MPa

Structural Material: Korean Reduced Activation Ferritic/ Martensitic (KO-RAFM) steel

Tritium Recovery: He purge

- SiC coated, graphite pebble bed reflector improves neutron economy (reduced leakage) and thus reduces the amount of Be multiplier needed. This is a cost and resource management advantage.
- Basis of ITER TBM design

Recent references:

Seungyon Cho et al., "Design and R&D progress of Korean HCCR TBM," *Fusion Engineering and Design*," **89**, p. 1137 (2014).

Seungyon Cho et al., "Overview of Helium Cooled Ceramic Reflector Test Blanket Module Development in Korea," *Fusion Engineering and Design*, **88**, p. 621 (2013).

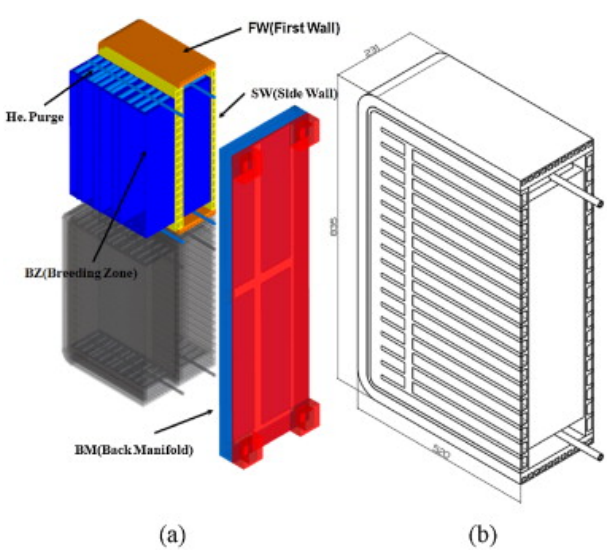

Fig. A1. Concept of the HCCR TBM (a), and a sub-module (b)

China Helium Cooled Ceramic Breeder (HCCB)

Proponent: China

Breeding Material: Li_4SiO_4 pebble bed (enriched to 80% ^6Li)

Multiplier: Be pebble bed

Coolant: Helium

Structural Material: China's Reduced Activation Ferritic Martensitic (RAFM) CLF-1 steel

Tritium Recovery: He purge

- Primary option for China's ITER TBM design

Recent references:
K.M. Feng et al., "New progress on design and R&D for solid breeder test blanket module in China," *Fusion Engineering and Design*," in press (2014).

Paper Highlights:

- The new progress on design and R&D of Chinese solid breeder TBM are introduced.
- The mock-up fabrication and component tests for Chinese HCCB TBM have being developed.
- The neutron multiplier Be pebbles, tritium breeder Li_4SiO_4 pebbles, and structural material CFL-1 are being prepared.
- The fabrication of 1/3 sized mock-up is being carried-out.
- The key technology development is proceeding on to the large-scale mock-up fabrication.

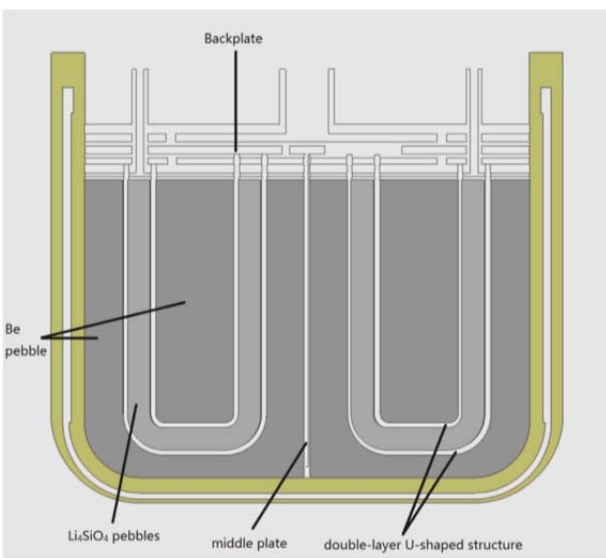

Fig. A2. Structural view of sub-module.

Dual Cooled Lithium Lead (DCLL) with Flow Channel Inserts (FCI)

Proponent: US (also backup concept for EU DEMO, but not for the ITER Test Blanket System)

Breeding Material: PbLi (84 wt% Pb, 16 wt% Li, enriched to 90% ^{6}Li)

Multiplier: Pb in PbLi

Coolant: Helium (8 MPa) for first wall and structures, PbLi secondary coolant

Structural Material: F82H RAFM

Tritium Recovery: Recovered from slip stream off PbLi coolant via vacuum pumping on permeation windows.

- SiC Flow channel insert will allow high PbLi coolant outlet temperature in power plant designs giving improved thermal efficiency

Recent references:

Damien Sutevski, Sergey Smolentsev, Mohamed Abdou, "3D numerical study of pressure equalization in MHD flow in a rectangular duct with insulating flow channel insert, *Fusion Engineering and Design* **89**, 1370 (2014).

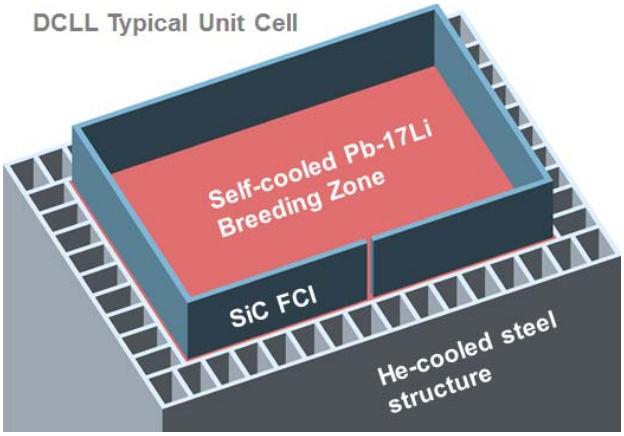

Fig. A3. DCLL unit cell configuration.

He Cooled Lithium Lead (HCLL)

Proponent: EU

Breeding Material: PbLi (84 wt% Pb, 16 wt% Li, enriched to 90% ^{6}Li)

Multiplier: Pb in PbLi

Coolant: Helium (8 MPa) for first wall, structures, and PbLi breeder

Structural Material: Eurofer RAFM

Tritium Recovery: Recovered from PbLi that slowly circulates out of TBB via vacuum pumping on permeation windows.

Recent references:
L.V. Boccaccini, et al., "Present status of the conceptual design of the EU Test Blanket Systems, *Fusion Engineering and Design* (2011), doi:10.1016/j.fusengdes.2011.02.036.

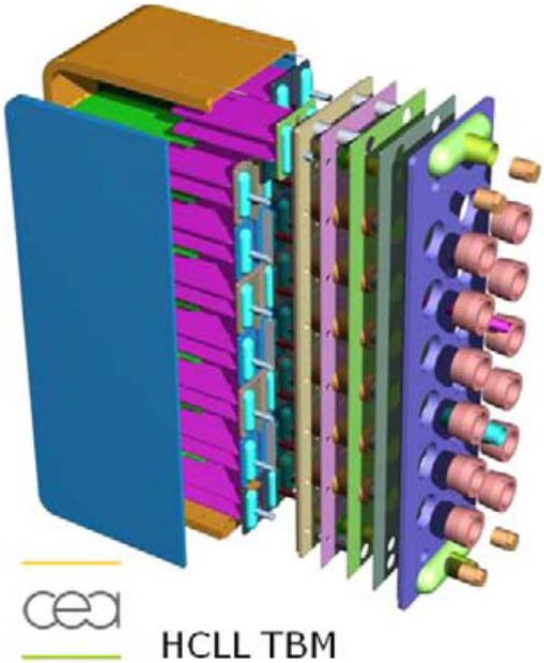

Fig. A4. European HCLL ITER Test Blanket System (TBS) configuration.

Helium Cooled Pebble Bed (HCPB)

Proponent: EU

Breeding Material: Li_4SiO_4 (30% 6Li) or Li_2TiO_3 (60% ^6Li)

Multiplier: Be pebble bed

Coolant: Helium (8 MPa)

Structural Material: Eurofer RAFM

Tritium Recovery: He purge through pebble bed in blanket

- One of two top candidates for EU Demo

Recent references:
L.V. Boccaccini, et al., "Present status of the conceptual design of the EU Test Blanket Systems, *Fusion Engineering and Design* (2011), doi:10.1016/j.fusengdes.2011.02.036.

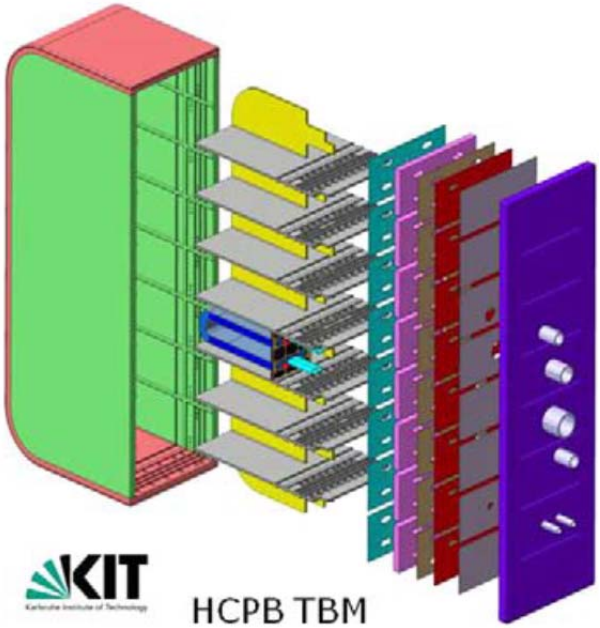

Fig. A5. EU HCPB design for ITER TBS.

Water Cooled Ceramic Breeder (WCCB)

Proponent: Japan (back-up DEMO concept for EU)

Breeding Material: Li_2TiO_3 (30% ^6Li)

Multiplier: Be pebble bed

Coolant: Pressurized water

Structural Material: FH82 RAFM

Tritium Recovery: He purge

- T permeation barriers used to prevent T permeation into water
- Considered for Demo

Recent references:
M. Enoeda et al., "Development of the Water Cooled Ceramic Breeder Test Blanket Module in Japan," *Fusion Engineering and Design*," **87**, p. 1363 (2012).

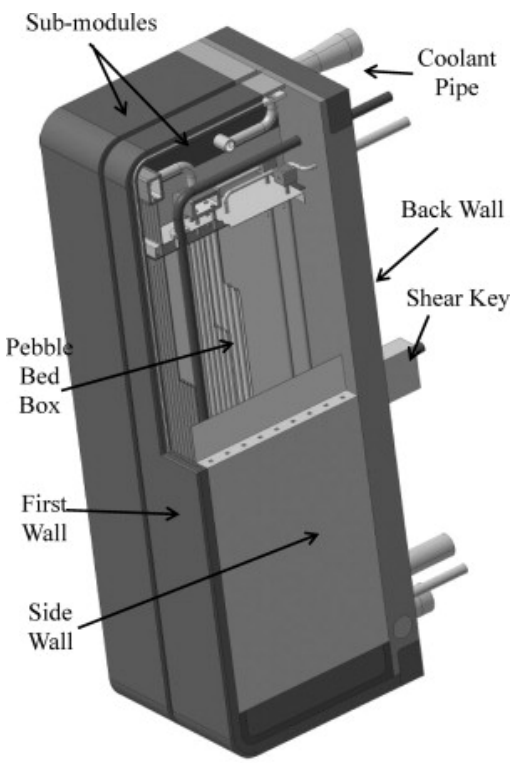

Fig. A6. Japanese ITER TBS WCCB design CAD model.

Appendix B

Comparison Criteria

The comparison criterial used in this report are listed here (See Table 5.5, Section 5):

1. Tritium Supply (TS): Produces more T fuel than is consumed in a manner that allows for continuous recovery. Ease of obtaining a TBR > 1 is desirable.
2. Power Handling (POW): Absorbs fusion power and makes it available to the power conversion system at high temperature. Low coolant pumping power is desirable.
3. Safety (SAF): Operates safely in normal and off-normal conditions.
4. Costs (COST): Has acceptable capital and operating costs.
5. Reliability (REL): Operates with high reliability leading to high availability.
6. Environmental (ENV): Has low environmental impact from radioactive waste.
7. Tritium extraction (TEX): Ease of tritium recovery from the breeder is favored.
8. Fabricability (FAB): Can be fabricated with standard, proven methods.

S. Malang et al. used the following criteria in Ref. B-1:

A. Engineering complexity of the design (EC)
B. Magneto-hydrodynamic issues (MHD)
C. Tritium extraction and control (TXC)
D. Compatibility issues (CI)
E. Pumping power (PP)
F. Achievable efficiency in the power conversion system (EFF)
G. Required Li-6 enrichment to achieve tritium self-sufficiency (TSS)
H. Potential for liquid metal (LM)/water reaction (LMR)
I. Required extrapolation of the present technologies (development risks) DR
J. Potential for extrapolation to more advanced concepts (AC)

Table B.1 shows how the criterial used by Malang map onto the criteria used in this report. As indicated, everything considered by Malang is included by one or more of the top level criteria used here.

Table B.1 Mapping Malang Criteria to Meier Criteria

Meier criteria→	1. TS	2. POW	3. COST	4. SAF	5. REL	6. ENV	7. TEX	8. FAB
Malang criteria								
A. EC			X		X			X
B. MHD		X						
C. TXC	X			X			X	
D. CI		X				X		x
E. PP		X			X			
F. EFF		X						
G. TSS	X		X					
H. LMR				X				
I. DR								x
J. AC		X						

Reference

B-1 S. Malang, A. R. Raffray, and N. B. Morley, "An example pathway to a fusion power plant system based on lead–lithium breeder: Comparison of the dual-coolant lead–lithium (DCLL) blanket with the helium-cooled lead–lithium (HCLL) concept as initial step," *Fusion Eng. Des.*, vol. 84, no. 12, pp. 2145–2157, Dec. 2009.

Appendix C
Concept Comparison and Ranking

Comparison Criteria

Consider eight comparison criteria based on key system requirements and stakeholder expectations (see text of report):
TS = Tritium Supply: Produces more T fuel than is consumed in a manner that allows for

continuous recovery. Ease of obtaining a TBR > 1 is desirable.
POW = Power Handling: Absorbs fusion power and makes it available to the power conversion system at high temperature. Low coolant pumping power is desirable.
SAF = Safety: Operates safely in normal and off-normal conditions.
COST = Costs: Has acceptable capital and operating costs.
REL = Reliability: Operates with high reliability leading to high availability.
ENV = Environmental: Has low environmental impact from induced radioactivity.
TEX = Tritium extraction: Ease of tritium recovery from the breeder is favored.
FAB = Fabricability: Can be fabricated with standard, proven methods.

Determine Criteria Weights

Use pair-wise comparison technique from Analytic Hierarchy Process (AHP) to determine criteria weights. (see http://en.wikipedia.org/wiki/Analytic_hierarchy_process)
Create a comparison matrix with the numbers in Row-i Column-j assigned according to the statement, "Row-i is [enter scale number] compared to Col-j"

Where the scale is:
1. equally important
2. moderately more important
3. strongly more important
4. very strongly more important
5. extremely more important

$ORIGIN := 1$

$i := 1, 2 .. 8$

$j := 1, 2 .. 8$

$$Criteria := \begin{array}{c} \begin{array}{cccccccc} TS & POW & COST & SAF & REL & ENV & TEX & FAB \end{array} \\ \begin{pmatrix} 1 & 2 & 2 & 3 & 4 & 4 & 3 & 5 \\ 0.5 & 1 & 1 & 4 & 2 & 2 & 3 & 4 \\ 0.5 & 1 & 1 & 5 & 3 & 2 & 4 & 5 \\ 0.333 & 0.25 & 0.2 & 1 & 0.2 & 0.333 & 0.333 & 0.25 \\ 0.25 & 0.5 & 0.333 & 5 & 1 & 2 & 2 & 4 \\ 0.25 & 0.5 & 0.5 & 3 & 0.5 & 1 & 2 & 4 \\ 0.333 & 0.333 & 0.25 & 3 & 0.5 & 0.5 & 1 & 4 \\ 0.2 & 0.25 & 0.2 & 4 & 0.25 & 0.25 & 0.25 & 1 \end{pmatrix} \end{array} \begin{array}{l} \\ TS \\ POW \\ COST \\ SAF \\ REL \\ ENV \\ TEX \\ FAB \end{array}$$

Square the matrix

$$SquareCr := Criteria \cdot Criteria$$

$$SquareCr = \begin{pmatrix} 7.998 & 12.999 & 11.682 & 85 & 23.35 & 27.749 & 38.249 & 72.75 \\ 5.631 & 7.999 & 7.016 & 55.5 & 13.3 & 15.832 & 21.832 & 44.5 \\ 6.747 & 9.332 & 7.999 & 68.5 & 15.25 & 18.915 & 25.415 & 53.75 \\ 1.185 & 1.806 & 1.682 & 7.997 & 3.228 & 3.527 & 4.344 & 7.629 \\ 4.548 & 5.749 & 4.966 & 42.415 & 7.999 & 10.331 & 14.247 & 30.165 \\ 3.59 & 4.666 & 4.067 & 35.75 & 7.1 & 7.999 & 11.249 & 24.5 \\ 3.006 & 3.832 & 3.316 & 29.581 & 5.598 & 6.497 & 7.997 & 16.997 \\ 2.165 & 2.433 & 2.121 & 13.35 & 3.45 & 4.157 & 4.982 & 8 \end{pmatrix}$$

Sum each row

$$ValueCr_i := \sum_{j=1}^{8} SquareCr_{i,j}$$

$$ValueCr = \begin{pmatrix} 279.8 \\ 171.6 \\ 205.9 \\ 31.4 \\ 120.4 \\ 98.9 \\ 76.8 \\ 40.7 \end{pmatrix} \begin{matrix} TS \\ POW \\ COST \\ SAF \\ REL \\ ENV \\ TEX \\ FAB \end{matrix}$$

Normalize the results

$$SumCr := \sum_{i=1}^{8} ValueCr_i \qquad SumCr = 1.026 \times 10^3$$

$$NormCr := \frac{ValueCr}{SumCr} \qquad NormCr = \begin{pmatrix} 0.273 \\ 0.167 \\ 0.201 \\ 0.031 \\ 0.117 \\ 0.096 \\ 0.075 \\ 0.04 \end{pmatrix} \begin{matrix} TS \\ POW \\ COST \\ SAF \\ REL \\ ENV \\ TEX \\ FAB \end{matrix}$$

This is the first iteration of the relative wieghts.

Square again to determine if the results are consistent

$$\text{Square2Cr} := \text{SquareCr} \cdot \text{SquareCr}$$

$$\text{Square2Cr} = \begin{pmatrix} 795 & 1058 & 931 & 6966 & 1661 & 1963 & 2569 & 5053 \\ 483 & 645 & 569 & 4217 & 1019 & 1202 & 1573 & 3082 \\ 572 & 765 & 674 & 4980 & 1209 & 1425 & 1864 & 3644 \\ 97 & 130 & 114 & 873 & 205 & 243 & 321 & 637 \\ 334 & 450 & 397 & 2918 & 716 & 844 & 1104 & 2155 \\ 273 & 367 & 324 & 2376 & 584 & 689 & 901 & 1757 \\ 213 & 289 & 255 & 1865 & 462 & 544 & 713 & 1393 \\ 124 & 169 & 149 & 1120 & 271 & 320 & 423 & 836 \end{pmatrix}$$

Sum each row

$$\text{Value2Cr}_i := \sum_{j=1}^{8} \text{Square2Cr}_{i,j}$$

$$\text{Value2Cr} = \begin{pmatrix} 20996 \\ 12790 \\ 15132 \\ 2620 \\ 8919 \\ 7271 \\ 5732 \\ 3414 \end{pmatrix} \begin{matrix} \text{TS} \\ \text{POW} \\ \text{COST} \\ \text{SAF} \\ \text{REL} \\ \text{ENV} \\ \text{TEX} \\ \text{FAB} \end{matrix}$$

Normalize results for second calculation of criteria weights.

$$\text{Sum2Cr} := \sum_{i=1}^{8} \text{Value2Cr}_i \qquad \text{Sum2Cr} = 7.687 \times 10^4$$

$$\text{Norm2Cr} := \frac{\text{Value2Cr}}{\text{Sum2Cr}} \qquad \text{Norm2Cr} = \begin{pmatrix} 0.273 \\ 0.166 \\ 0.197 \\ 0.034 \\ 0.116 \\ 0.095 \\ 0.075 \\ 0.044 \end{pmatrix} \begin{matrix} \text{TS} \\ \text{POW} \\ \text{COST} \\ \text{SAF} \\ \text{REL} \\ \text{ENV} \\ \text{TEX} \\ \text{FAB} \end{matrix}$$

Comparing this results to the initial normalized criteria weights shows that result are very close.

$$\text{Norm2Cr} - \text{NormCr} = \begin{pmatrix} 0 \\ -0.001 \\ -0.004 \\ 0.003 \\ -0.001 \\ -0.002 \\ -0 \\ 0.005 \end{pmatrix}$$

So the criteria weightings are now consistent. Tritium supply is the most important criteria with Safety second and Power Extractgion third. Fabrication is the least important criteria.

Concept Comparison

Now compare seven TBB concepts.

Name: Breeder / Multiplier / Coolant / Structure
LV = Lithium/Vanadium: Li / none / Li / V
WCLL = Water Cooled Lead Lithium: PbLi / Pb in PbLi / water / FMS
HCLL = He Cooled Lead Lithium: PbLi / Pb in PbLi / He / FMS
DCLL = Dual Cooled Lead Lithium: PbLi / Pb in PbLi / PbLi and He / FMS
DCLL-F = DCLL with FCI: PbLi / Pb in PbLi / PbLi and He / FMS with FCI
MS = Molten Salt: Flibe / Be in Flibe / Flibe / ODS
HCPB = He Cooled Pebble Bed: Ceramic Breeder / Be / He / FMS

Relative wieghting scale

The rating of the concepts was done on the following scale relative to the DCLL concept.

Ability/ease of meeting the given expectation/requirement compared to the DCLL is:
1 = Much lower / much harder
2 = Moderately lower / moderately harder
3 = Roughly comparable
4 = Moderately better / moderately easier
5 = Much better / much easier.

Concept Comparison Matrix

Cols. 1-7 = TS POW COST SAF REL ENV TEX FAB

$$\text{ConceptCom} := \begin{pmatrix} 4 & 4 & 1 & 1 & 3 & 4 & 2 & 1 \\ 1 & 1 & 2 & 4 & 4 & 3 & 3 & 4 \\ 3 & 2 & 2 & 2 & 2 & 3 & 3 & 2 \\ 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 \\ 3 & 4 & 3 & 2 & 3 & 3 & 3 & 2 \\ 2 & 3 & 3 & 3 & 3 & 4 & 3 & 1 \\ 2 & 4 & 4 & 2 & 2 & 4 & 2 & 2 \end{pmatrix} \begin{matrix} \text{LV} \\ \text{WCLL} \\ \text{HCLL} \\ \text{DCLL} \\ \text{DCLL-F} \\ \text{MS} \\ \text{HCPB} \end{matrix}$$

Multiply the concept score matrix above by the weighting vector to determine the concept ranking.

$$\text{Rank} := \text{ConceptCom} \cdot \text{Norm2Cr} = \begin{pmatrix} 2.909 \\ 2.119 \\ 2.442 \\ 3 \\ 3.088 \\ 2.733 \\ 2.916 \end{pmatrix} \begin{matrix} \text{LV} \\ \text{WCLL} \\ \text{HCLL} \\ \text{DCLL} \\ \text{DCLL-F} \\ \text{MS} \\ \text{HCPB} \end{matrix}$$

Normalize the ranking result.

$$\text{SumRank} := \sum_{i=1}^{7} \text{Rank}_i \qquad \text{SumRank} = 19.206$$

$$\text{NormRank} := \frac{\text{Rank}}{\text{SumRank}}$$

Ranking Result

$$\text{NormRank} = \begin{pmatrix} 0.151 \\ 0.11 \\ 0.127 \\ 0.156 \\ 0.161 \\ 0.142 \\ 0.152 \end{pmatrix} \begin{matrix} \text{LV} \\ \text{WCLL} \\ \text{HCLL} \\ \text{DCLL} \\ \text{DCLL-F} \\ \text{MS} \\ \text{HCPB} \end{matrix}$$

The DCLL with FCI is the highest ranking concept, but it is only marinally higer than the DCLL. The HCPB and LV concepts are close to each other and slightly lower than the the first two. The WCLL is the lowest ranking.

Appendix D

Bibliography of Articles Related to Tritium Breeding Blankets

M. Abdou, D. Sze, C. Wong, M. Sawan, A. Ying1, N. B. Morley, "U.S. Plans and Strategy for ITER Blanket Testing," *Fusion Sci. Technol.*, vol. 47, pp. 475–487, 2005.

M. Abdou, APEX Team, A. Ying, N. Morley, K. Gulec, S. Smolentsev, M. Kotschenreuther, S. Malang, S. Zinkle, T. Rognlien, P. Fogarty, B. Nelson, R. Nygren, K. McCarthy, M. . Youssef, N. Ghoniem, D. Sze, C. Wong, M. Sawan, H. Khater, R. Woolley, R. Mattas, R. Moir, S. Sharafat, J. Brooks, a Hassanein, D. Petti, M. Tillack, M. Ulrickson, and T. Uchimoto, "On the exploration of innovative concepts for fusion chamber technology," *Fusion Eng. Des.*, vol. 54, no. 2, pp. 181–247, Feb. 2001.

A. Aures, L. W. Packer, and S. Zheng, "Tritium self-sufficiency of HCPB blanket modules for DEMO considering time-varying neutron flux spectra and material compositions," *Fusion Eng. Des.*, vol. 88, no. 9–10, pp. 2436–2439, Oct. 2013.

L. V. Boccaccini, a. Aiello, O. Bede, F. Cismondi, L. Kosek, T. Ilkei, J.-F. Salavy, P. Sardain, and L. Sedano, "Present status of the conceptual design of the EU test blanket systems," *Fusion Eng. Des.*, vol. 86, no. 6–8, pp. 478–483, Oct. 2011.

B. Bornschein, C. Day, D. Demange, and T. Pinna, "Tritium management and safety issues in ITER and DEMO breeding blankets," *Fusion Eng. Des.*, vol. 88, no. 6–8, pp. 466–471, Oct. 2013.

C. Bustreo, G. Casini, G. Zollino, T. Bolzonella, and R. Piovan, "FRESCO, a simplified code for cost analysis of fusion power plants," *Fusion Eng. Des.*, vol. 88, no. 12, pp. 3141–3151, Dec. 2013.

D. Carloni and L. Boccaccini, "Requirements for helium cooled pebble bed blanket and R&D activities," *Fusion Eng. Des.*, 2014.

S. Cho, M.-Y. Ahn, D. W. Lee, Y.-H. Park, E. H. Lee, J. S. Yoon, T. K. Kim, C. W. Lee, Y.-H. Yoon, S. K. Kim, H. G. Jin, K. I. Shin, Y. Il Jung, Y. H. Jeong, Y. O. Lee, D. Y. Ku, C.-S. Kim, S. C. Park, I.-K. Yu, and K. Jung, "Overview of Helium Cooled Ceramic Reflector Test Blanket Module development in Korea," *Fusion Eng. Des.*, vol. 88, no. 6–8, pp. 621–625, Oct. 2013.

S. Cho, M. Ahn, D. Lee, and Y. Park, "Design and R&D progress of Korean HCCR TBM," *Fusion Eng. Des.*, 2014.

G. Dell'Orco, A. Ancona, and P. Di Maio, "Experimental tests on Li-ceramic breeders for the helium cooled pebble bed (HCPB) blanket design," *Fusion Eng. Des.*, vol. 69, pp. 233–240, 2003.

M. Enoeda, H. Tanigawa, T. Hirose, S. Suzuki, K. Ochiai, C. Konno, Y. Kawamura, T. Yamanishi, T. Hoshino, M. Nakamichi, H. Tanigawa, K. Ezato, Y. Seki, A. Yoshikawa, D. Tsuru, and M. Akiba, "Development of the Water Cooled Ceramic Breeder Test Blanket Module in Japan," *Fusion Eng. Des.*, vol. 87, no. 7–8, pp. 1363–1369, Aug. 2012.

K. Feng, G. Zhang, G. Hu, and Y. Chen, "New progress on design and R&D for solid breeder test blanket module in China," *Fusion Eng. Des.*, 2014.

F. Franza and A. Ciampichetti, "Sensitivity Study for Tritium Permeation in Helium-Cooled Lead-Lithium DEMO Blanket with the FUS-TPC Code," *Fusion Sci. Technol.*, pp. 631–635, 2013.

M. Fütterer, H. Albrecht, and P. Giroux, "Tritium technology for blankets of fusion power plants," *Fusion Eng. Des.*, vol. 50, pp. 735–743, 2000.

A. M. Garofalo, M. a. Abdou, J. M. Canik, V. S. Chan, A. W. Hyatt, D. N. Hill, N. B. Morley, G. a. Navratil, M. E. Sawan, T. S. Taylor, C. P. C. Wong, W. Wu, and A. Ying, "A Fusion Nuclear Science Facility for a fast-track path to DEMO," *Fusion Eng. Des.*, Apr. 2014.

L. M. Giancarli, M. Abdou, D. J. Campbell, V. a. Chuyanov, M. Y. Ahn, M. Enoeda, C. Pan, Y. Poitevin, E. Rajendra Kumar, I. Ricapito, Y. Strebkov, S. Suzuki, P. C. Wong, and M. Zmitko, "Overview of the ITER TBM Program," *Fusion Eng. Des.*, vol. 87, no. 5–6, pp. 395–402, Aug. 2012.

B. G. Hong, D. W. Lee, S. J. Wang, Y. Kim, W. K. In, and K. H. Yoon, "Basic concepts of DEMO and a design of a helium-cooled molten lithium blanket for a testing in ITER," *Fusion Eng. Des.*, vol. 82, no. 15–24, pp. 2399–2405, Oct. 2007.

Y. Kang and T. Terai, "Moderate tritium properties in lithium–tin alloy as a liquid breeder/ coolant," *Fusion Eng. Des.*, vol. 81, no. 1–7, pp. 519–523, Feb. 2006.

V. Kapyshev, I. Danilov, I. Kartashev, V. Kovalenko, a. Leshukov, V. Poliksha, a. Razmerov, Y. Strebkov, M. Sviridenko, E. Trusova, N. Vladimirova, and a. Kalashnikov, "Initial design and test of the tritium breeder monitoring system for the lead-lithium cooled ceramic breeder (LLCB) module of the ITER," *Fusion Eng. Des.*, vol. 88, no. 9–10, pp. 2293–2297, Oct. 2013.

K. Kim, H. C. Kim, S. Oh, Y. S. Lee, J. H. Yeom, K. Im, G.-S. Lee, G. Neilson, C. Kessel, T. Brown, and P. Titus, "A preliminary conceptual design study for Korean fusion DEMO reactor," *Fusion Eng. Des.*, vol. 88, no. 6–8, pp. 488–491, Oct. 2013.

Y. Kim, B. G. Hong, and C. H. Kim, "A neutronic investigation of He-cooled liquid Li-breeder blankets for fusion power reactor," *Fusion Eng. Des.*, vol. 75–79, pp. 1067–1070, Nov. 2005.

I. Kirillov, "Lithium cooled blanket of RF DEMO reactor," *Fusion Eng. Des.*, vol. 49–50, pp. 457–465, 2000.

M. Kwon, Y. S. Na, J. H. Han, S. Cho, H. Lee, I. K. Yu, B. G. Hong, Y. H. Kim, S. R. Park, and H. T. Seo, "A strategic plan of Korea for developing fusion energy beyond ITER," *Fusion Eng. Des.*, vol. 83, no. 7–9, pp. 883–888, Dec. 2008.

D. W. Lee, B. G. Hong, S. K. Kim, and Y. Kim, "Design and preliminary safety analysis of a helium cooled molten lithium test blanket module for the ITER in Korea," *Fusion Eng. Des.*, vol. 83, no. 7–9, pp. 1217–1221, Dec. 2008.

D. Lee, J. Yoon, K. Jung, and S. Kim, "Preliminary Study on the Melting and Reaction of Liquid Metal Breeders for a Korean Test Blanket Module in ITER," *Fusion Sci. Technol.*, pp. 171–179, 2012.

E. Lee, S. Kim, J. Yoon, D. Lee, and S. Cho, "Progress of Tritium Extraction and Measurement Methods Development from Liquid Breeder Blanket in Korea," *Fusion Sci. Technol.*, pp. 77–82, 2012.

A. Li Puma, J. L. Berton, B. Brañas, L. Bühler, J. Doncel, U. Fischer, W. Farabolini, L. Giancarli, D. Maisonnier, P. Pereslavtsev, S. Raboin, J.-F. Salavy, P. Sardain, J. Szczepanski, and D. Ward, "Breeding blanket design and systems integration for a helium-cooled lithium–lead fusion power plant," *Fusion Eng. Des.*, vol. 81, no. 1–7, pp. 469–476, Feb. 2006.

A. Li Puma, C. Bachmann, L. V Boccaccini, P. Norajitra, G. Aiello, J. Aubert, D. Carloni, and C. Mistrangelo, "Design and Development of Demo Blanket Concepts in Europe," Presented at ISFNT-11, Barcelona, Sept. 17, 2013.

S. Malang, M. Tillack, C.P.C. Wong, N. Morley, S. Smolentsev, "Development of the lead lithium (DCLL) blanket concept," *Fusion Sci. Technol.*, vol. 60, pp. 249–256, 2011.

S. Malang, a. R. Raffray, and N. B. Morley, "An example pathway to a fusion power plant system based on lead–lithium breeder: Comparison of the dual-coolant lead–lithium (DCLL) blanket with the helium-cooled lead–lithium (HCLL) concept as initial step," *Fusion Eng. Des.*, vol. 84, no. 12, pp. 2145–2157, Dec. 2009.

S. Malang and R. Mattas, "Comparison of lithium and the eutectic lead-lithium alloy, two candidate liquid metal breeder materials for self-cooled blankets," *Fusion Eng. Des.*, vol. 27, pp. 399–406, 1995.

H. Matsuura, H. Nakaya, Y. Nakao, S. Shimakawa, M. Goto, S. Nakagawa, and M. Nishikawa, "Evaluation of tritium production rate in a gas-cooled reactor with continuous tritium recovery system for fusion reactors," *Fusion Eng. Des.*, vol. 88, no. 9–10, pp. 2219–2222, Oct. 2013.

R. Mattas, D. Smith, C. Reed, and J. Park, "Results of R and D for lithium/vanadium breeding blanket design," *Fusion Eng. Des.*, vol. 39–40, pp. 659–668, 1997.

B. Merrill, "Challenges Leading to a FNSF." Presented to FESAC Materials Science Panel, Dec. 7, 2011.

E.A. Mogahed and G.L Kulcinski, “Bibliography of a Promising Tritium Breeding Material - Pb83Li17,” Univ. of Wisc. Report UWFDM-994, 1995.

H. Moriyama, S. Tanaka, and D. Sze, “Tritium recovery from liquid metals,” *Fusion Eng. Des.*, vol. 28, pp. 226–239, 1995.

K. Okano, G. Federici, and K. Tobita, “DEMO design activities in the broader approach under Japan/EU collaboration,” *Fusion Eng. Des.*, pp. 4–8, Apr. 2014.

Y. Park, I. Yu, M. Ahn, S. Cho, and D. Ku, “Fabrication OF Li_4SiO_4 Pebbles using Slurry Droplet Wetting Method for Solid Breeding Material,” *Fusion Sci. Technol.*, pp. 185–189, 2012.

Y. Poitevin, “The Tritium Breeding Blankets for Fusion Reactors - A key component for sustainability of Fusion Energy,” Presentation at Swiss Nuclear Forum, March 23, 201.

Y. Poitevin, L. V. Boccaccini, M. Zmitko, I. Ricapito, J.-F. Salavy, E. Diegele, F. Gabriel, E. Magnani, H. Neuberger, R. Lässer, and L. Guerrini, “Tritium breeder blankets design and technologies in Europe: Development status of ITER Test Blanket Modules, test & qualification strategy and roadmap towards DEMO,” *Fusion Eng. Des.*, vol. 85, no. 10–12, pp. 2340–2347, Dec. 2010.

Y. Poitevin, L. V. Boccaccini, M. Zmitko, I. Ricapito, J.-F. Salavy, E. Diegele, F. Gabriel, E. Magnani, H. Neuberger, R. Lässer, and L. Guerrini, “Tritium breeder blankets design and technologies in Europe: Development status of ITER Test Blanket Modules, test & qualification strategy and roadmap towards DEMO,” *Fusion Eng. Des.*, vol. 85, no. 10–12, pp. 2340–2347, Dec. 2010.

Y. Poitevin and L. Boccaccini, “The European breeding blankets development and the test strategy in ITER,” *Fusion Eng. Des.*, vol. 79, pp. 741–749, 2005.

A. R. Raffray, “Future Developments : Blanket Technology and Material Engineering for FNT.” pp. 1–23, 2013.

A.R. Raffray, S. Malang, L. El-Guebaly, X. Wang, “Ceramic Breeder Blanket for ARIES-CS,” *Fusion Sci. Technol.*, vol. 47, no. May, pp. 1068–1073, 2005.

A. Raffray, M. Akiba, V. Chuyanov, L. Giancarli, and S. Malang, “Breeding blanket concepts for fusion and materials requirements,” *J. Nucl. Mater.*, vol. 307–311, pp. 21–30, Dec. 2002.

I. Ricapito, A. Ciampichetti, and R. Lässer, “Tritium Extraction from Liquid Pb-16Li: A Critical Review of Candidate Technologies for ITER and DEMO Applications,” *Fusion Sci. Technol.*, pp. 1159–1162, 2011.

N. Roux, J. Avon, a. Floreancing, J. Mougin, B. Rasneur, and S. Ravel, “Low-temperature tritium releasing ceramics as potential materials for the ITER breeding blanket,” *J. Nucl. Mater.*, vol. 233–237, pp. 1431–1435, Oct. 1996.

N. Roux, S. Tanaka, C. Johnson, and R. Verrall, “Ceramic breeder material development,” *Fusion Eng. Des.*, vol. 41, no. 1–4, pp. 31–38, Sep. 1998.

S. Sharafat, N. Ghoniem, M. Sawan, A. Ying, and B. Williams, “Breeder foam: an innovative low porosity solid breeder material,” *Fusion Eng. Des.*, vol. 81, no. 1–7, pp. 455–460, Feb. 2006.

S. Sharafat and N. Ghoniem, “Cellular foams: a potential innovative solid breeder material for fusion applications,” *Fusion Sci. Technol.*, vol. 47, no. May, pp. 6–10, 2005.

K. I. Shin, D. W. Lee, E. H. Lee, S.-K. Kim, J. S. Yoon, and S. Cho, “Design and performance analysis of structural components for a Korean He Cooled Ceramic Reflector TBM in ITER,” *Fusion Eng. Des.*, vol. 88, no. 9–10, pp. 1866–1871, Oct. 2013.

D. L. Smith, C. C. Baker, and D. A. I. K. A. I. Sze, “Overview of the Blanket Comparison And Selection Study,” *Fusion Technol.*, vol. 8, pp. 10–44, 1985.

Y. Someya, H. Takase, H. Utoh, K. Tobita, C. Liu, and N. Asakura, “Simplification of blanket system for SlimCS fusion DEMO reactor,” *Fusion Eng. Des.*, vol. 86, no. 9–11, pp. 2269–2272, Oct. 2011.

D. Stork, “Materials R & D for a timely DEMO: Key Findings and Recommendations of the EU Roadmap Materials Assessment Group,” Presented at ISFNT-11, Barcelona, Sept. 16-20, 2013.

K. Tobita, S. Nishio, A. Saito, and M. Enoeda, “Water-cooled solid breeding blanket for DEMO,” *Proceeding ITC18, 2008*, pp. 285–288, 2009.

S. Tosti and A. Pozio, “Hydrogen solubility and electrical resistivity measurements of hydrogenated Pb-Li,” 2013.

C. P. C. Wong, M. Abdou, M. Dagher, Y. Katoh, R. J. Kurtz, S. Malang, E. P. Marriott, B. J. Merrill, K. Messadek, N. B. Morley, M. E. Sawan, S. Sharafat, S. Smolentsev, D. K. Sze, S. Willms, a. Ying, and M. Z. Youssef, “An overview of the US DCLL ITER-TBM program,” *Fusion Eng. Des.*, vol. 85, no. 7–9, pp. 1129–1132, Dec. 2010.

C. P. C. Wong, S. Malang, M. Sawan, M. Dagher, S. Smolentsev, B. Merrill, M. Youssef, S. Reyes, D. K. Sze, N. B. Morley, S. Sharafat, P. Calderoni, G. Sviatoslavsky, R. Kurtz, P. Fogarty, S. Zinkle, and M. Abdou, “An overview of dual coolant Pb–17Li breeder first wall and blanket concept development for the US ITER-TBM design,” *Fusion Eng. Des.*, vol. 81, no. 1–7, pp. 461–467, Feb. 2006.

I. Yamamoto, T. Nishitani, A. Sagara, “Overview of Recent Japanese Activities and Plans in Fusion Technology,” *Fusion Sci. Technol.*, vol. 52, pp. 347–356, 2007.

A. Ying, J. Reimann, L. Boccaccini, M. Enoeda, M. Kamlah, R. Knitter, Y. Gan, J. G. Van Der Laan, L. Magielsen, P. A. Di Maio, G. D. Orco, R. Kumar, J. T. Van Lew, H. Tanigawa, and S. Van Til, “Status of ceramic breeder pebble bed thermo-mechanics R&D and impact on breeder material mechanical strength,” *Fusion Eng. Des.*, vol. 87, no. 7–8, pp. 1130–1137, 2012.

D. Youchison and S. N. Laboratories, “Flow Instabilities in Helium-cooled Porous Media and the Helium Micro-Jet Array alternative to the HEMJ” Presented at US-Japan High Heat Flux Component Workshop, Livermore, Jan. 8, 2014.

S. J. Zinkle, J. P. Blanchard, R. W. Callis, C. E. Kessel, R. J. Kurtz, P. J. Lee, K. a. McCarthy, N. B. Morley, F. Najmabadi, R. E. Nygren, G. R. Tynan, D. G. Whyte, R. S. Willms, and B. D. Wirth, “Fusion materials science and technology research opportunities now and during the ITER era,” *Fusion Eng. Des.*, Mar. 2014.

H. Zohm, “Assessment of DEMO challenges in technology and physics,” *Fusion Eng. Des.*, vol. 88, no. 6–8, pp. 428–433, Oct. 2013.