Lessons learned for the Breeding Blanket designers from the design development of the European Test Blanket Module Systems

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Goals/Content of the talk

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1. **To recall the basic features of the main Breeding Blanket Concepts for DEMO; to recall the scope of the TBM Project; to summarize the main features of the European TBS Design**

First part of the presentation: **Breeding Blanket / ITER TBM Project**

2. **To discuss design issues/solutions** encountered along the conceptual design of the European TBS that can be already brought to the attention of the DEMO breeding blanket designers

Second part of the presentation: **Lessons Learned for DEMO Breeding Blanket development**

Breeding Blanket / ITER TBM Project

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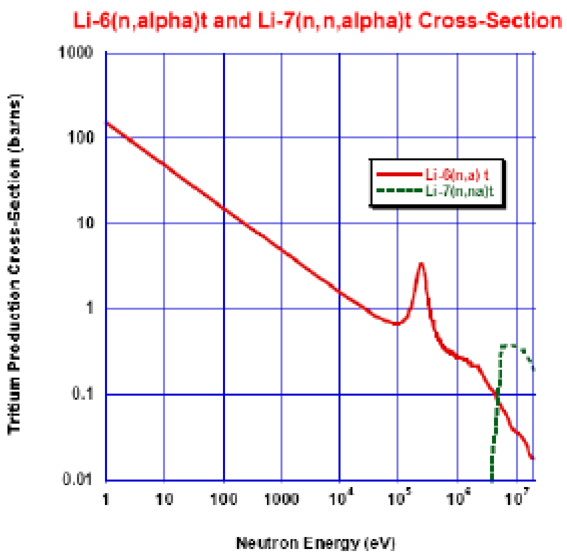
Functions of the Breeding Blanket

A. Tritium breeding to achieve the tritium self-sufficiency

B. Nuclear to thermal power conversion and heat extraction

C. Neutron/γ-ray shielding

Function A

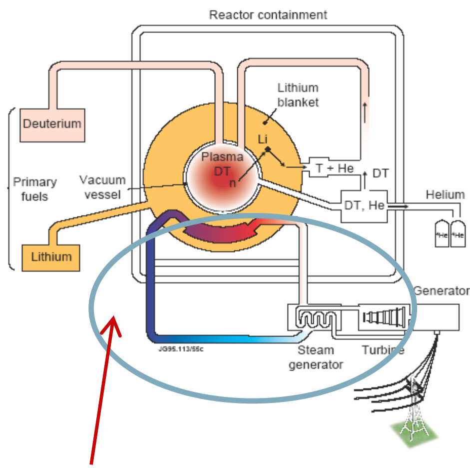


In the plasma: T + D → ^{4}He + **n** (17.6 MeV)

^{6}Li + n → ^{3}T + ^{4}He + 4.8 MeV

^{7}Li + n → ^{3}T + ^{4}He + n - 2.8 MeV

Function B

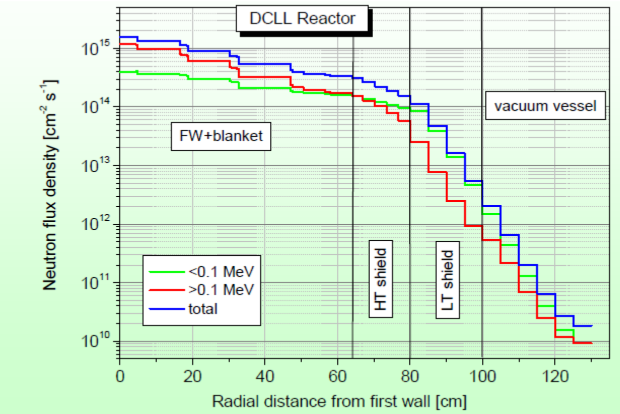


Breeding blanket materials are heated-up because:

a) Heat flux from plasma
b) Nuclear heat generated by neutrons slowing-down and nuclear reactions with Li.

The thermal power is then extracted by a suitable coolant and **converted into electrical power** through a conventional turbine-alternator group

Function C



Neutron flux radially has to decrease of at least 1 order of magnitude to protect VV and magnets

Breeding Blanket / ITER TBM Project

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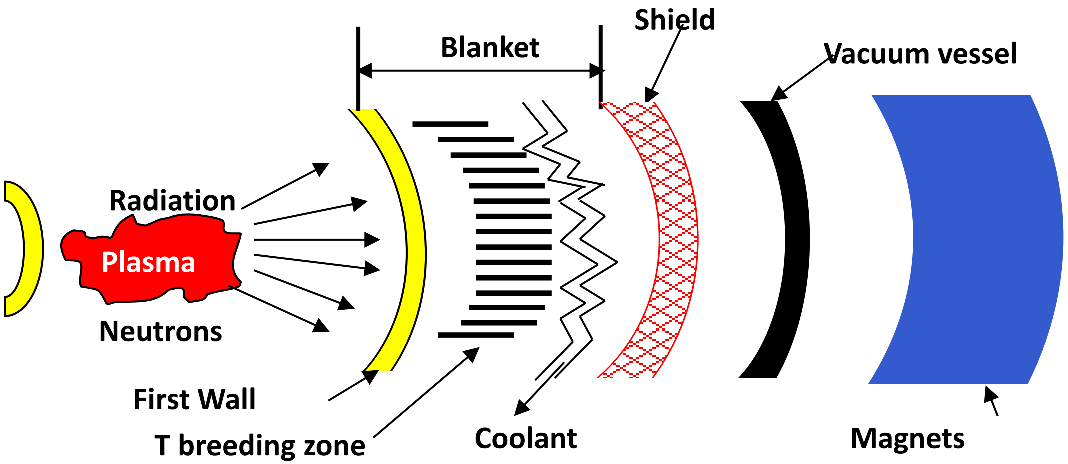
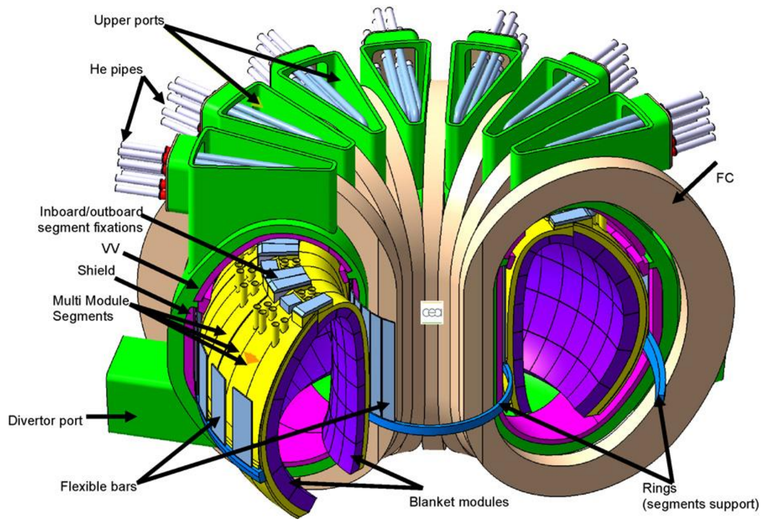
Any Breeding Blanket (BB) consists of:

- Li bearing breeding material
- neutron multiplier
- structural material
- coolant



Any acceptable combination has to be satisfactory with respect to:

- safety requirements
- performance requirements
  - tritium self sufficiency
  - net plant efficiency



HCLL-DEMO reactor (2007, CEA)

Breeding Blanket / ITER TBM Project

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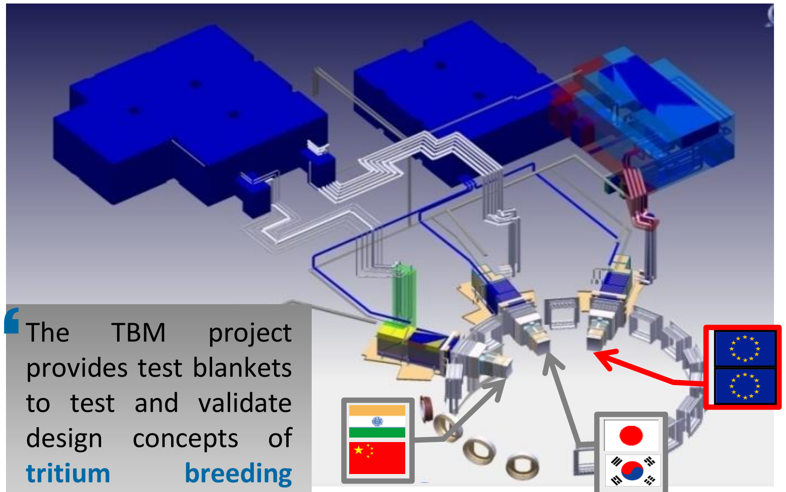
Blanket type	WCLL	HCLL	HCCB	WCCB	LLCB	DCLL	Molten Salt	Li-V	Adv. HCCB	SCLL	Li Evap.
Structural material	RAFM	RAFM	RAFM	RAFM	RAFM	RAFM + ODS	Ferritic Steel	V alloy (+ insulation)	SiCf/SiC	SiCf/SiC	W alloy
Breeder	Pb-16Li (liquid)	Pb-16Li (Liquid)	Li_4SiO_4, Li_2TiO_3 (pebbles)	Li_2TiO_3 (pebbles)	Pb-16Li (liquid) + Li_2TiO_3 (pebbles)	Pb-16Li (liquid)	FLiBe (liquid)	Li (nat.)	Li_2TiO_3, Li_2O (pebbles)	Pb-16Li (liquid)	Li (nat.)
Neutron Multiplier			Be (pebbles)	Be (pebbles)			Be (pebbles)		Be (pebbles)		
Coolant	H_2O (15 MPa)	He (8 MPa)	He (8 MPa)	PWR and Supercritical H_2O (15.5 - 25 MPa)	He (8 MPa)	He (8 MPa) + Pb-16Li	FLiBe (liquid)	Li (nat.)	He (10 MPa)	Pb-16Li	Li (nat.) evap.
T coolant	265 - 325	300 - 500	300 - 500	290 - 520	325 - 500	300 - 480 (He) 460 - 700 (PbLi)	450 - 550	330 - 610	600 - 900	765 - 1100	1100 - 1200
T Structural material	265 - 550	300 - 550	300 - 550	290 - 550	300 - 550	300 - 550	max. 550	330 - 700	700 - 1150	765 - 1000	max. 1300
Reactor concept studies	PPCS-A	PPCS-AB	PPCS-B	SSTR	DEMO-S	ARIES-ST APEX PPCS-C	FFHR-2	ARIES-RS	DREAM A-SSTR2	ARIES-AT TAURO	APEX-EVOLVE

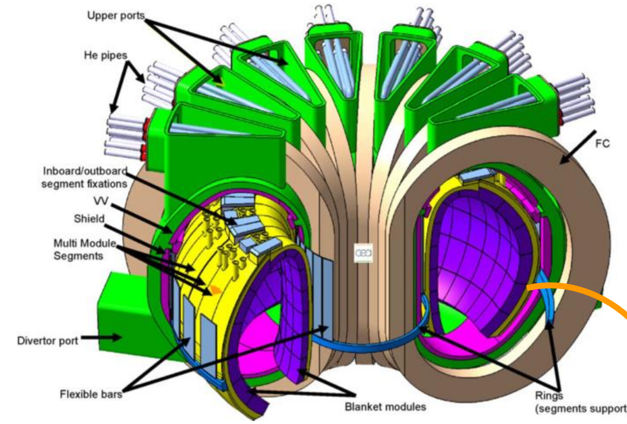
Breeding Blanket / ITER TBM Project

TBM Program in ITER

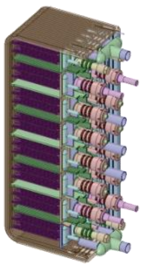
3rd ITER Council (2008) established the TBM program in ITER



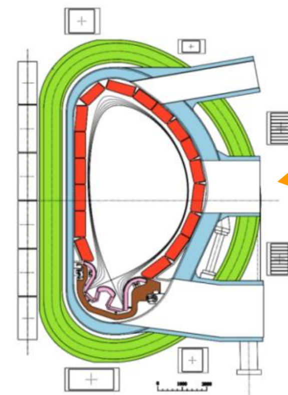
> The TBM project provides test blankets to test and validate design concepts of **tritium breeding blankets** relevant to a power-producing reactor.



HCLL-DEMO



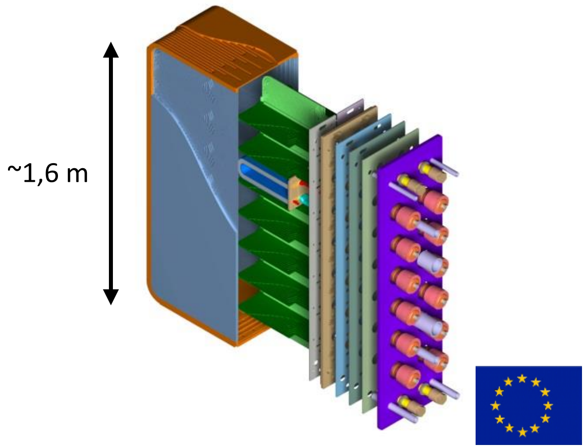
HCLL-TBM



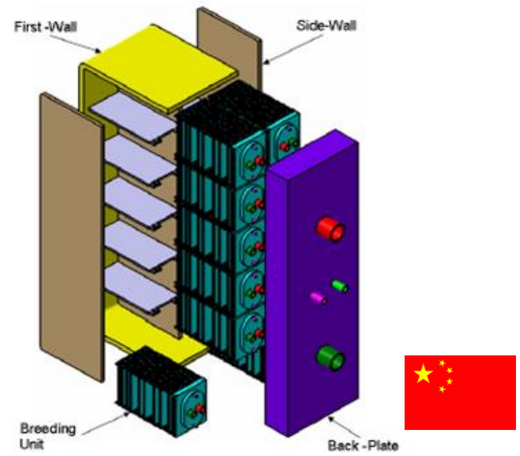
Test in ITER

- through a test environment (Test Blanket Module) that reproduces the operating conditions foreseen in a DEMO Breeding Blanket
- through systems that adopts technologies that are relevant for a DEMO BB when compatible with ITER operational requirements
- through the development and validation of predictive modelling tools that are needed for the design of a DEMO BB

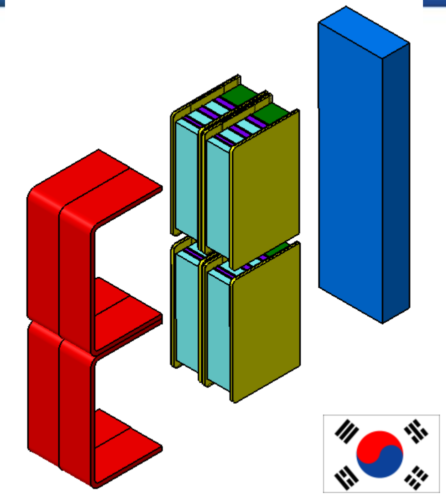
Breeding Blanket / ITER TBM Project



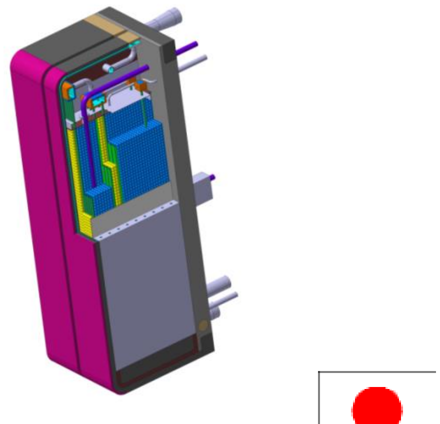
Helium-Cooled Pebble-Bed



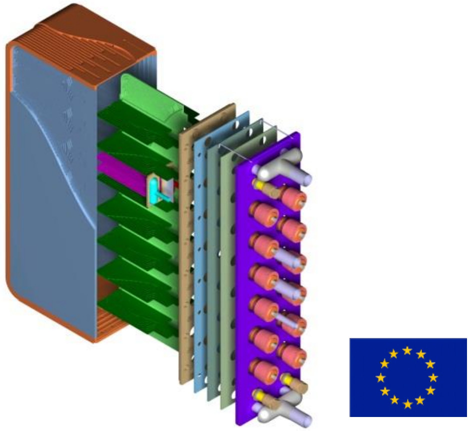
Helium-Cooled Ceramic Breeder



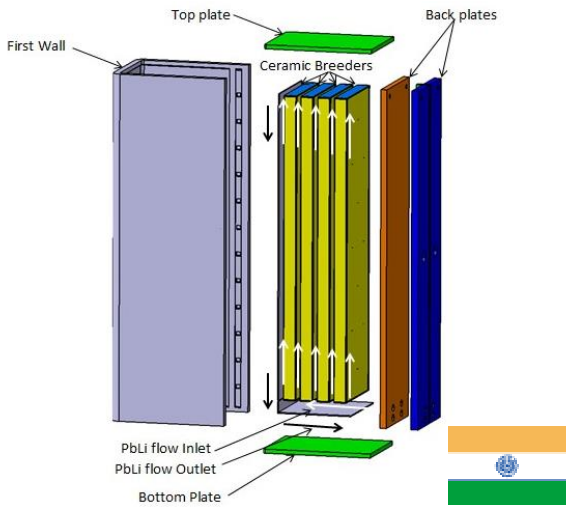
Helium-Cooled Ceramic Reflector



Water-Cooled Ceramic Breeder



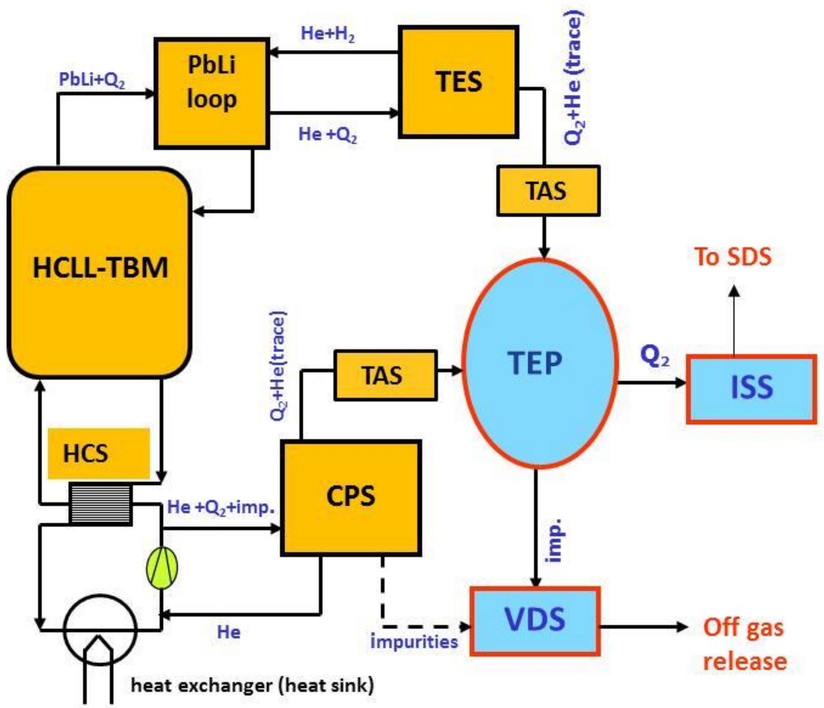
Helium-Cooled Lead-Lithium

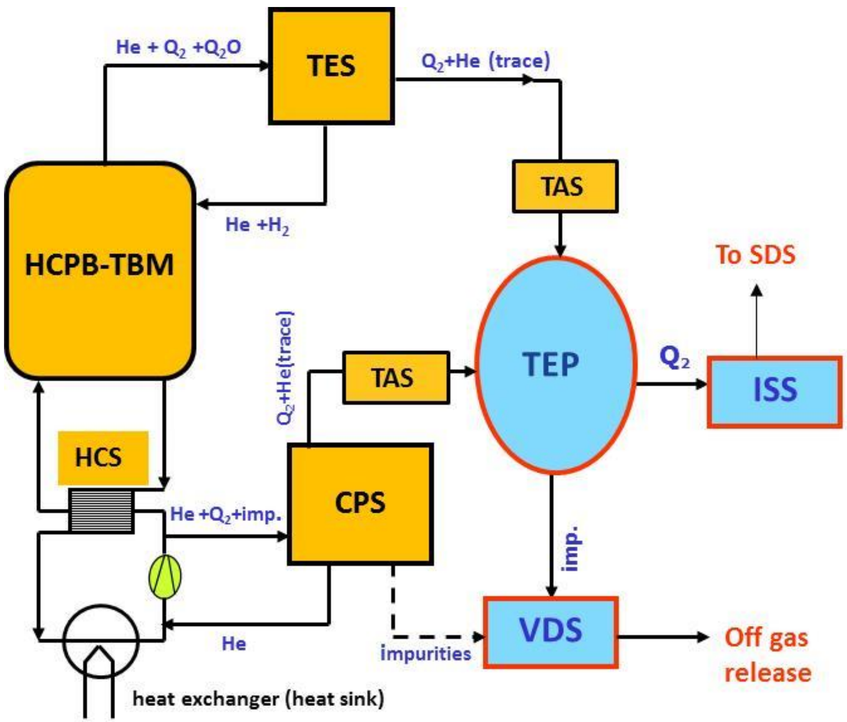


Lead-Lithium Ceramic-Breeder

Breeding Blanket / ITER TBM Project

European HCLL and HCPB-TBS





Breeding Blanket System

TES: Tritium Extraction System

CPS: Coolant Purification System

HCS: Helium Cooling System

Fuel Cycle

TEP: Tokamak Exhaust Processing System

ISS: Isotope Separation System

VDS: Vent Detritiation System

Lessons learned: Introduction

As the conceptual design phase of the HCLL and HCPB-TBS has been concluded and we have entered the first stage of the preliminary design phase, there is already a significant RoX (Return on Experience) which can be delivered to the DEMO designers.

Here we'll focus not on generic recommendations but on **four examples of specific technical points** that the Breeding Blanket designers can already "take on board".

These four examples deal with:

1. Licensing Procedure and impact on the design
2. Design of the Instrumentation
3. Definition and implementation of the Safety Functions
4. A specific integration issue: the problem of the tritium contamination

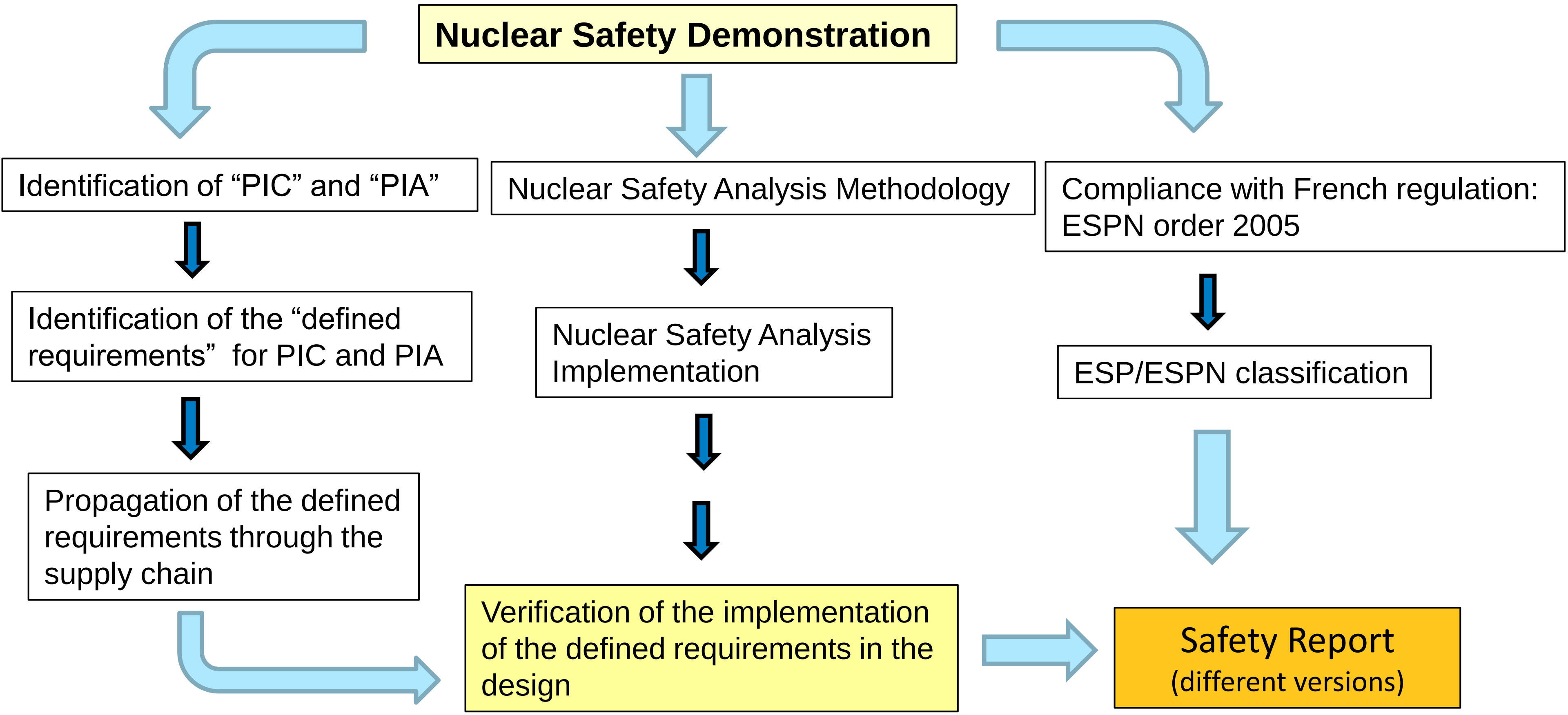
Lessons learned: Licensing Process

- In order to get the license to operate, the **Operator -** ITER Organization - is requested, *among many others commitments, prescriptions and demands from the regulator -* to carry out a **Nuclear Safety Demonstration** (part of the Safety Demonstration) in which the risks originated from the ITER operation are identified together with the provisions to prevent or limit them

- As per the French BNI order December 2012 these provisions are ensured by components identified as **PIC** (Protection Important Components). **PIA** (Protection Important Activities) are the processes of design, construction, installation and testing of PIC

- As per the BNI order, **PIC/PIA must be strictly identified, controlled and reported**

Lessons learned: Licensing Process



Lessons learned: Licensing Process

Licensing process and impact on the design

Safety/ESP/ESPN classification of the main components of the HCPB-TBS Coolant Purification System

Equipment ID	Description	Type	Fluid	Fluid/Group Fluid	Safety Class	Quality Class	Normal operating temperature of fluid, °C	Maximum allowable temperature of fluid, °C	Design temperature of fluid, °C	Normal operating pressure, MPa	Maximum allowable pressure, Bar PS	Design Pressure, MPa	Volume, m^3 V	DN for piping	Radioactivity concentration, GBq/m^3 Av	Total radioactivity for vessels, GBq V*Av	Pressure category as defined in PE or NPE	Nuclear level as defined in NPE
56A2HP-FI-2001 56A2HP-FI-2004	Filter	Accessory	gas	Gas/Group 2	SIC-2	QC1	90	450	90	8.1	101	10.1	0.0013	N/A	3.54E-03	4.60E-06	II	No NPE
56A2HP-HX-2001	Economizer	vessel	gas	Gas/Group 2	SIC-2	QC1	90-250	500	500	8.1	101	10.1	0.009	N/A	3.54E-03	3.19E-05	II	No NPE
				Gas/Group 2	SIC-2	QC1	120-280	500	500	8.1	101	10.1	0.005	N/A	<1e-3	<5e-6		
56A2HP-TA-2005 56A2HP-TA-2009	Oxidizing Bed	vessel	gas	Gas/Group 2	SIC-2	QC1	250	500	500	8.1	101	10.1	0.04	N/A	3.54E-03	1.42E-04	IV	No NPE
56A2HP-HX-2002	Cooler	vessel	gas	Gas/Group 2	SIC-2	QC1	35-250	500	500	8.1	101	10.1	0.003	N/A	3.54E-03	1.06E-05	II	No NPE
			liquid water	liquid/group 2	SIC-2	QC1	10	10	30-40	0.8	16	1.6	0.01	N/A	0	0.00E+00		
56A2HP-TA-2007 56A2HP-TA-2001	Q_2O PTSA	vessel	gas	Gas/Group 2	SIC-2	QC1	35-300	500	500	8	101	10.1	0.00764	N/A	1.70E+02	3.90E-01	II	N3
56A2HP-HX-2004	Economizer	vessel	gas	Gas/Group 2	SIC-2	QC1	35-155	500	500	8	101	10.1	0.009	N/A	<1e-03	1.25E-03	II	No NPE
					SIC-2	QC1	280-400	500	500	8	101	10.1	0.009	N/A	<1e-03	1.25E-03		
56A2HP-HT-2004	Heater	vessel	gas	Gas/Group 2	SIC-2	QC1	155-400	500	500	8	101	10.1	0.005	N/A	<1e-03	<5e-06	II	No NPE
56A2HP-TA-2003 56A2HP-TA-2004	Heated (impurity) getters	vessel	gas	Gas/Group 2	SIC-2	QC1	400	500	500	7.9	101	10.1	0.15	N/A	<1e-03	<1.5e-04	IV	No NPE

Lessons learned: Licensing Process

Recommendations

1. **To identify PIC/PIA and related defined requirements** already in the conceptual design, securing their propagation into the supplier chain

2. **To carry out at early stage of the design the ESP/ESPN classification** of the main components as this impacts the both design and manufacturing requirements. A reliable classification requires much effort. A close collaboration with a Notified Body is strongly recommended not only for the classification but for the general understanding of the ESP/ESPN constraints and requirements (*conformity assessment, essential safety requirements*)

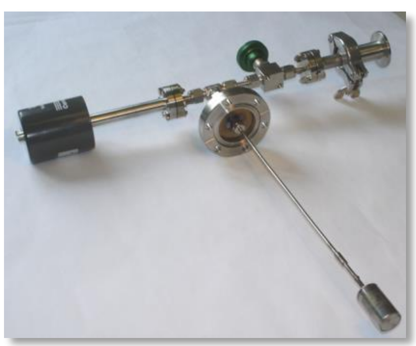
3. **To obtain relevant experimental data for the validation of the safety codes** in a wide application domain that covers both fusion related phenomena and specific plant parameter range. *Example of this is the recent experimental activity carried out at ENEA (Italy) to simulate an In-TBM LOCA and subsequent correlation of the results with RELAP 5*

Lessons learned: Instrumentation Design

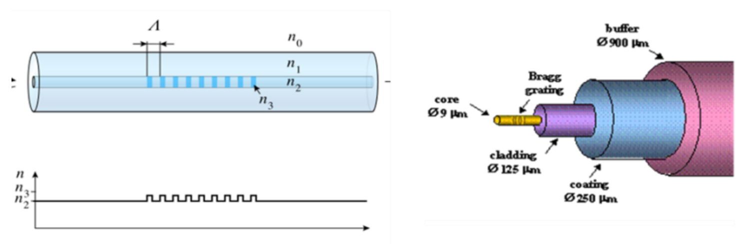
TBS instrumentation must perform reliably in the ITER challenging environmental conditions. Depending on the sub-system, the number of physical parameters and range of measurement in the TBM set and ancillary systems is vast.

- temperature, 300÷900 ˚C, for TBM structural and functional materials and ancillary system process fluids
- mass flow-rate of the process fluids, from few Nl/s to some thousand Nl/s
- pressure of the process fluids, from ambient pressure up to 8 MPa
- magnetic field, up to 5 Tesla in the TBM location
- electrical current, up to several thousand A for the eddy currents
- neutron flux, up to 10^{18} n/m^2 s in the TBM
- neutron spectrum, from eV to MeV
- gamma radiation field, from10^{-5} to some Sv/h
- displacement/position, from 10^{-3} to some mm
- tritium concentration/partial pressure, from 10^{-2} to 10^{2} Pa, in the process fluids

Permeation based sensors



Temperature and strain measurement with distributed fiber optic arrays (regenerated FGB sensors)



Lessons learned: Instrumentation Design

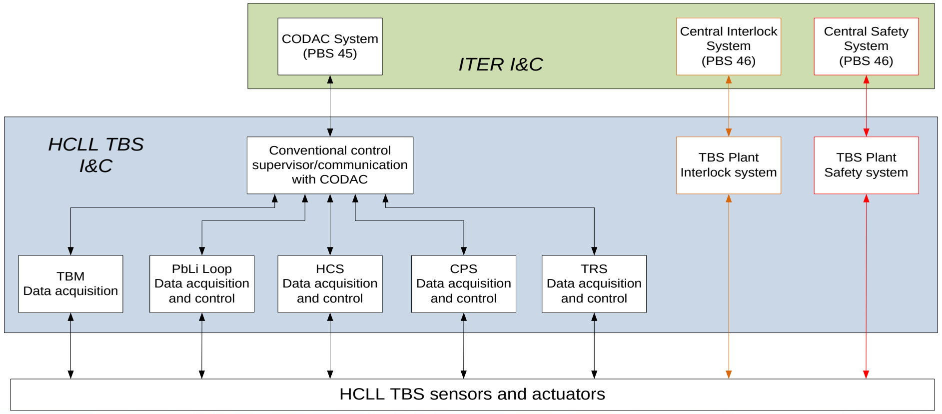
Main challenges on instrumentation:

- **Radiation Field**, both direct from plasma and secondary emission from activated materials
- **Magnetic Field** effects

Both fields can cause drift in the sensor signals and degradation of accuracy, with impact on the machine availability

Following the ITER recommendation, sensors and related instrumentation chain **have been categorized in three tiers**, depending on their functions:

- **safety**
- **investment protection**
- **conventional control**



Depending on the tier to which they belong, different requirements in terms of accuracy, reliability, quality assurance, resistance to radiation, must be considered

Lessons learned: Instrumentation Design

Recommendations

a. To categorize at an early stage the instrumentation among the three tiers as this will allow to better identify the proper design requirements

b. To prepare soon accurate P&ID in order to have a full control of the instrumentation to be deployed in the different breeding blankets systems

c. To implement appropriate shielding provision on the electronics to avoid performance degradation due to radiation and magnetic field

d. To select sensors assuring high performance while reducing integration problems in case of limited space: example is the possible use of optical fibers instead of thermocouples in the breeding blanket modules

Lessons learned: Safety Functions

Three typologies of safety functions have been identified specifically for HCLL and HCPB-TBS:

1. **isolation of TBS sub-systems** to ensure radioactive inventory confinement
2. **pressure release** in case of over-pressurization of thee TBS sub-systems
3. **Plasma Shutdown (FPS)** requested by the TBS Plant Safety System to the Central Safety System

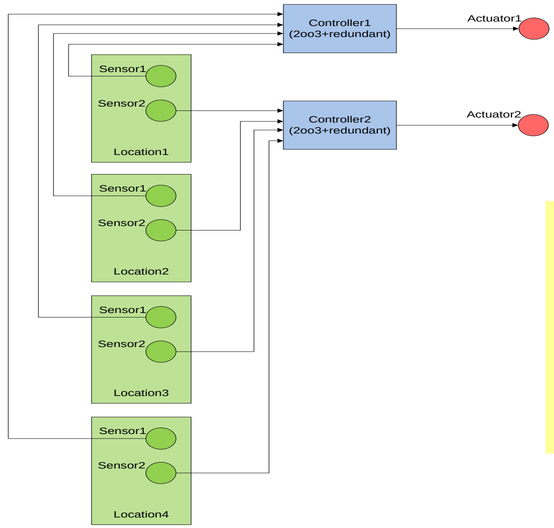
They are triggered upon detection of abnormal conditions by PIC instrumentation deployed in the different TBS sub-systems

Accident Scenario	Primary parameter(s) detected	Implemented HCLL-Safety Functions or single actions	FPS triggered by CSS
Ex-vessel LOCA	Pressure decrease in HCS	HCS circuit isolation	YES
In-TBM LOCA	Pressure increase in Pb-Li loop	- HCS circuit isolation function - PbLi circuit depressurization	YES
In-vessel LOCA	- Pressure decrease in HCS - Different in/out He flow-rate across TBM	-HCS circuit isolation -PbLi circuit isolation	YES
LOFA in HCS	- Low He mass flow-rate in HCS - Low current absorbed by He-circulator	HCS circuit isolation (if FPS is triggered)	YES
LOHS	Temperature difference increase across the HCS heat sink (heat exchanger	no functions/ actions if FPS is triggered	YES
Pb-Li loop pipe break	Pressure decrease in Pb-Li loop	Pb-Li circuit isolation	NO
TRS pipe break	Pressure decrease in TRS loop	TRS circuit isolation	NO
CPS pipe break	Pressure decrease in CPS loop	CPS circuit isolation	NO
HCS-PCS failure	Pressure increase in HCS	HCS circuit depressurization	YES

Lessons learned: Safety Functions

1. **Design of the Safety Functions against the single failure criterion**, implementing the principle of defense-in-depth, **requires the redundancy of safety devices,** sensors, actuators and I&C cubicles
2. **Use of 2oo3 logic** for sensors triggering the safety functions is highly recommendable to avoid that spurious signals may lead to unjustified shutdown of ITER

This architecture has been implemented in the current design of the HCLL and HCPB-TBS. *As an example, six pressure sensors, distributed in pair in three different locations, will trigger the closure of the HCS isolation valves in case of an ex-vessel LOCA.*



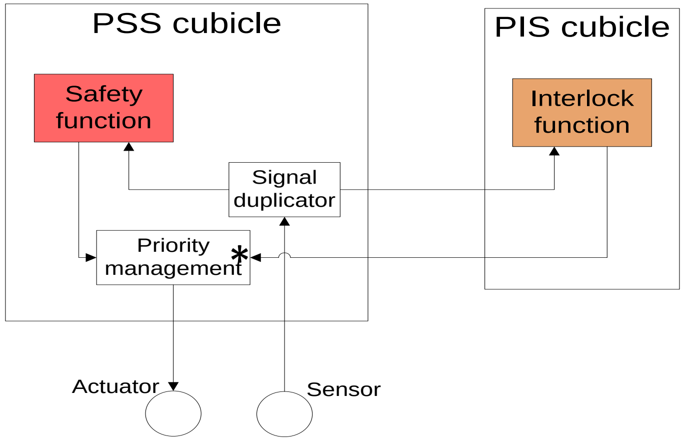
Taking into account that this approach is applied to all TBS sub-systems and to all PIC sensors, there will be a proliferation of sensors and cables in the Port Cell, with integration issues and lack of space

Lessons learned: Safety Functions

Recommendations

1. The identification of the Safety Functions and their implementation have to be considered early in the design. This implementation must be detailed, including the selection of the safety devices with the appropriate performance features

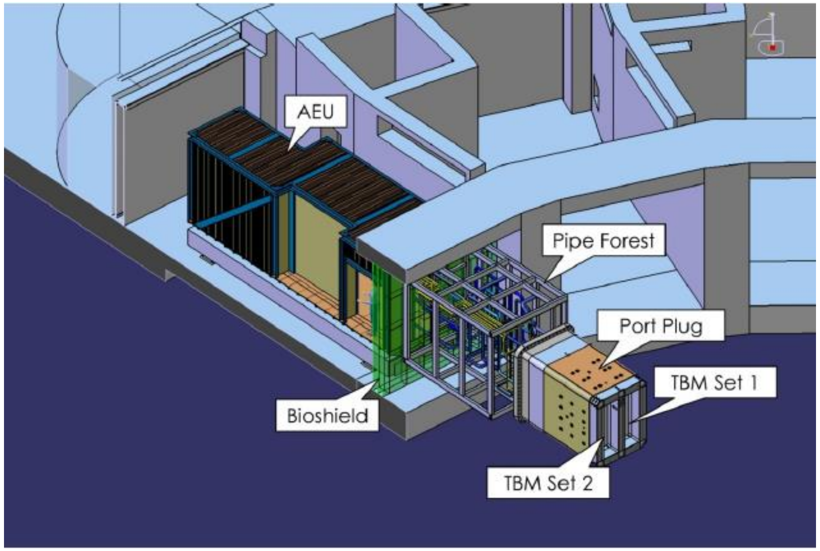
2. Using for the investment protection the same instrumentation adopted for the safety functions is a design solution for the two European TBS implementing a signal duplicator, located in the Plant Safety System (PSS) cubicle. This allows reducing the number of sensors, then lowering design effort, cost and integration issues



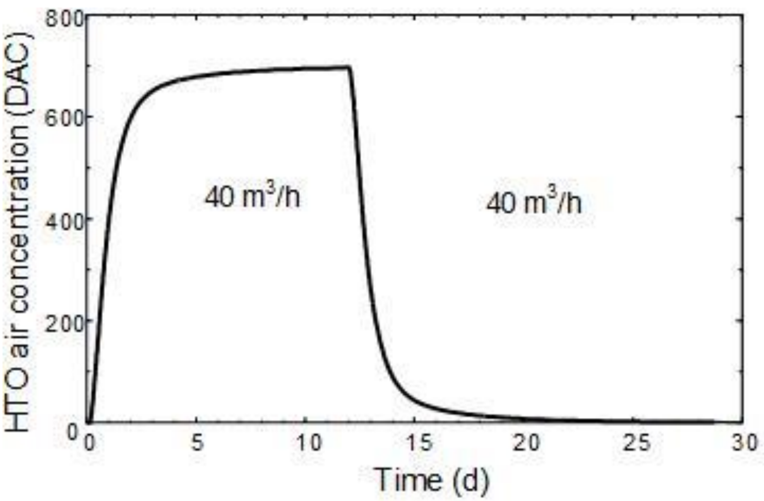
Lessons learned: Integration

Example of Integration Issue: **tritium contamination in the areas hosting the TBM systems**

- Difficulty to respect the authorized level of tritium concentration in the Port Cell #16 (maximum 1 DAC during operation/maintenance; 1 DAC due to tritium contamination: 3.4×10^5 Bq/m^3), where many components of HCLL and HCPB-TBS sub-systems are located
- This is mainly due to the high tritium permeation rate from these TBS components into the Port Cell, combined with low DS capacity
- Tritium absorbed in the epoxy painted walls is slowly released, challenging the possibility of having hands-on maintenance in the Port Cell



Generic Port Cell in ITER



Tritium concentration in the Port Cell#16 during operation and short term maintenance (curve by TMAP4)

Lessons learned: Integration

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Example of Integration Issue: **tritium contamination in the areas hosting the TBM systems**

Recommendations

1. to implement in the design provisions to strongly reduce the tritium permeated into the areas hosting the breeding blanket systems. For the Breeding Blankets based on Pb-16Li, they are:
   - design of a tritium extractor from Pb-16Li with high extraction efficiency (>80%) to lower the tritium partial pressure in the liquid metal, then reducing the tritium permeation rate into the plant areas
   - use of tritium permeation barriers on the inner walls of the piping
   - adoption of suitable operating conditions: i) PbLi flow-rate as high as possible to reduce the tritium partial pressure in Pb-16Li; high CPS flow-rate to keep low the tritium partial pressure in the main cooling system

2. to increase the DS recirculation rate, as the steady state tritium concentration in the air is inversely proportional to the DS flow-rate for a given tritium source rate

3. to focus on suitable liners to protect the concrete walls, ensuring a fast release of HT/HTO during the maintenance phase

SUMMARY

- **The conceptual design of HCLL and HCPB-TBM systems has been concluded** and the first part of the preliminary design phase in now approached. The technologies adopted in the different systems to fulfill the requested functions and top level design requirements have been selected. The main components have been sized and preliminary integration in the relevant ITER buildings implemented. Preliminary set of design and safety requirements have been identified

- **Contribution from TBM system design to the DEMO BB design is already relevant in terms of RoX**

- There are examples of outcomes from the design of HCLL and HCPB-TBS than can be already taken in account by the designers of a breeding blanket for DEMO. Four of them have been considered here. They deal with:
  - Licensing Procedure and impact on the design
  - Design of the Instrumentation
  - Definition and Implementation of the Safety Functions
  - A specific integration issue: the problem of the tritium contamination

- The **general recommendation** from these examples is to consider the related specific provisions, based on the outcomes of the TBM Project activities, already at the conceptual phase of the Breeding Blanket Design

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