

# TRL Assessment of Fusion Power Plant Subsystems

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# **Goal: Develop TRL's Based on Key Components/Subsystems Within the Different FESAC Themes**

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- **Start with the FESAC Theme C and Associated Issues: Harnessing Fusion Power as outlined in the FESAC issues listed next.**
- **Build on previous TRL effort but with a focus on components/subsystems.**



# Issues Relating to FESAC Theme C: Harnessing Fusion Power

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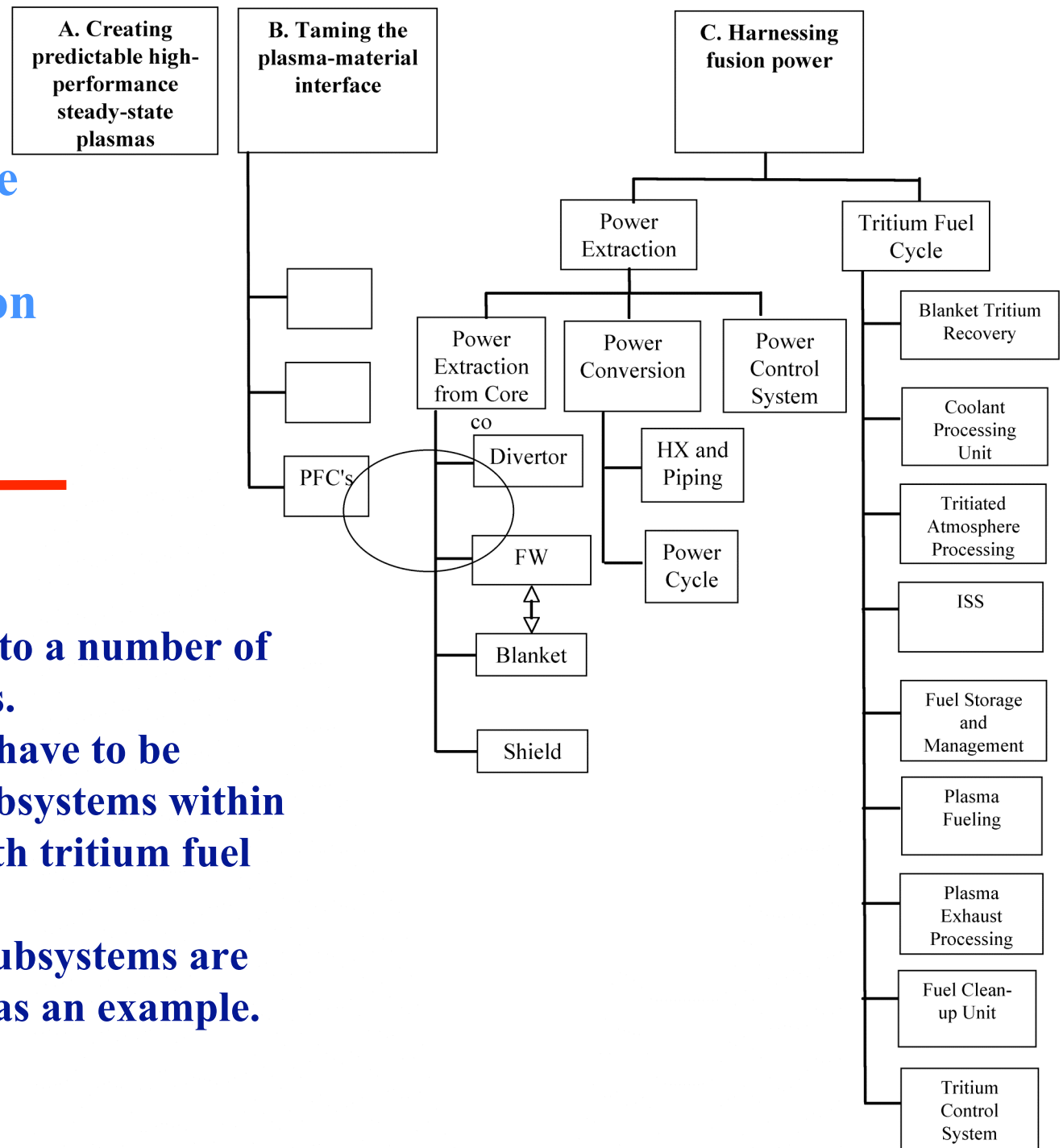
11. **Fusion Fuel Cycle:** *Learn and test how to manage the flow of tritium throughout the entire plant, including breeding and recovery.*
12. **Power Extraction:** *Understand how to extract fusion power at temperatures sufficiently high for efficient production of electricity or hydrogen.*
13. **Materials Science in the Fusion Environment:** *Understand the basic materials science for fusion breeding blankets, structural components, plasma diagnostics and heating components in high neutron fluence areas.*
14. **Safety:** *Demonstrate the safety and environmental potential of fusion power: to preclude the technical need for a public evacuation plan, and to minimize the environmental burdens of radioactive waste, mixed waste, or chemically toxic waste for future generations.*
15. **Reliability, Availability, Maintainability, Inspectability (RAMI):** *Demonstrate the productive capacity of fusion power and validate economic assumptions about plant operations by rivaling other electrical energy production technologies.*

# Key Systems under Theme C Include the Power Conversion/Extraction and Tritium Fuel Cycle Systems

- These can be divided into a number of subsystems/components.
- TRL definitions would have to be developed for all the subsystems within Theme C (need help with tritium fuel cycle subsystems).
- The power extraction subsystems are further described here as an example.



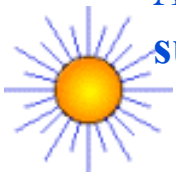
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# Power Conversion/Extraction Subsystems

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- **The power core extraction subsystems include:**
  - blanket
  - first wall (considered in many designs as integrated with the blanket)
  - divertor
  - shield
- **The functions of components/subsystems might overlap among different FESAC themes.**
  - e.g. the divertor and first wall as PFC's would fall under the FESAC Theme B (Taming the plasma-material interface) but also under the power extraction subsystems of Theme C.
- **Although the issues covered within the different FESAC themes might not correspond solely to a specific component/subsystem, they are covered within the functions and demands of the different subsystems.**
  - e.g. the functions of the blanket subsystem include energy transfer for power production but also tritium breeding and shielding.
  - Also, materials, safety and RAMI are integral part of the neutron power capture subsystems.



# Example TRL Development for Blanket Subsystem

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- The TRL method is a useful tool for quantitatively evaluating the readiness level of the blanket subsystem for a fusion power plant (DEMO and beyond)
- In order to develop these TRL definitions, it is important to consider the functions of the component/subsystem, the different environmental conditions under which it has to operate, and the related performance requirements, which need to be progressively integrated in the development path
- The TRL definitions need to be developed in at least two concept-specific stages.
  - The first stage consists of top-level design-independent definitions at the subsystem level, applicable to all possible concepts for the subsystem
  - Applying this set of TRL allows for a (preliminary) assessment of the overall readiness level of the subsystem.
  - A more detailed assessment of the readiness level of specific blanket concepts would then require the definition of a second stage of TRL's, allowing for a more focused evaluation of design-specific technology development for specific concepts.



# **The Blanket Subsystem Has to Fulfill its Functions under Demanding Operating Conditions**

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## **Main Functions:**

- The blanket must breed the tritium necessary for the continued operation of the power plant, and possibly for starting up another one.
- The kinetic energy of radiations (neutrons and gamma rays) has to be converted to thermal energy at a temperature level high enough for efficient generation of electrical energy in the power conversion system (or for hydrogen production).
- Radiation energy and flux have to be reduced in the blanket so that the radiation levels in the components behind the blanket (shield, VV and magnets) are acceptable over the lifetime of the plant.

## **Operating conditions:**

- High neutron flux defined by the maximum wall load of 14.1 MeV neutrons.
- Plasma radiation heat flux to the FW.
- High magnetic field strength and strong field gradients, defined by the toroidal and poloidal fields and the control coil field.
- High coolant temperatures necessary for efficient conversion from thermal to electrical energy in the power conversion system.
- High coolant velocities and pressures in case of gas cooling.
- Outside vacuum conditions requiring exceptionally high leak tightness since there is near-zero tolerance for blanket fluid leaks into the plasma chamber.

## **Additionally, the Following Performance and Operation Goals Are Required of the Blanket for a Safe and Attractive Power Plant**

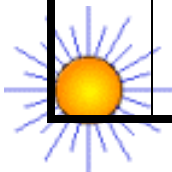
- **Accommodation of high power density in order to meet the economic goals of an attractive power plant.**
- **First wall and blanket must be able to accommodate a few plasma disruption annually without any damage.**
- **The blanket and its operation must meet the exceptionally high safety features required of the plant.**
  - **The T bred in the blanket must be released into the fuel cycle with a rate sufficiently high to maintain the T inventory in the blankets at an acceptable level.**
  - **All the materials contained in the blankets have to be confined reliably during normal operations as well as during postulated accidents.**
  - **Any release of radioactivity during normal operation must meet very stringent criteria.**
- **All materials used in the blanket must be suitable for unrestricted release, recycling or low shallow land burial (Class C or better).**
- **The blanket must be designed and fabricated to achieve very low capital cost to achieve the cost goals, while achieving all other design goals.**
- **The lifetime of the blankets must be sufficiently high for economic reasons (to reduce replacement cost, minimize down-time for blanket exchanges, maximize availability and reduce radwaste stream).**
- **The blankets must be designed for an exceptional high reliability and short replacement time in order to meet stringent availability goals. Unscheduled failures and methods to quickly get the plant operational are the most critical to maintain planned plant availability.**



# First-Stage Technology Readiness Levels for Blanket Subsystem

<b>Theme:</b>	<b>Harnessing Fusion Power</b>
<b>Subsystem:</b>	<b>Blanket</b>

<b>TRL</b>	<b>TRL Function</b>	<b>Generic Definition</b>	<b>Subsystem-Specific Definition</b>
1		Basic principles observed and formulated.	System studies to define tradeoffs and requirements on blanket subsystems: heat loads, tritium breeding, magnetic effects (MHD and magnetic loads under off-normal operation scenarios), material constraints (temperature, stress, tritium inventory, radiation effects).
2	Concept Development	Technology concepts and/or applications formulated.	Blanket concepts including breeding material, structural material and cooling configuration explored. Critical parameters characterized.
3		Analytical and experimental demonstration of critical function and/or proof of concept.	Data from coupon-scale experiments on heat loads (and thermal-hydraulic), tritium generation and mass transfer; modeling of governing heat transfer, thermal-hydraulic (including MHD) and mass transfer processes (tritium behavior and possibly corrosion) as demonstration of function of blanket concept.



# Definitions of First Stage TRL's

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## ***TRL 1: Basic principles observed and formulated***

The basic principles guiding the blanket environment in a fusion power plant are formulated. The magnitude, spatial and temporal variation of the heat loads, magnetic field and loads and tritium breeding are characterized and bounded, through system studies. The likely effect on the blanket behavior including heat and mass transfer mechanisms, thermal-hydraulic (MHD effects), and neutron irradiation effects are hypothesized and their relative importance estimated through system studies. Material constraints (temperature, stress, tritium inventory) are formulated.

## ***TRL 2: Technology concepts and/or applications formulated***

Potential blanket concepts that would provide the required functions of breeding, energy exchange and shielding are explored, including armor, structural material and coolant choices in integrated configurations. The critical properties and constraints affecting the design are characterized.

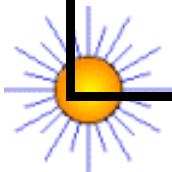
## ***TRL 3: Analytical and experimental demonstration of critical function and/or proof of concept***

Active R&D program is initiated in support of the concepts formulated at TRL-2. Experimental data from individual coupon-scale experiments on heat loads (and thermal-hydraulic), tritium generation and mass transfer for candidate blanket structural/breeding material concepts are obtained to demonstrate their potential ability to accommodate the the more severe fusion environment and provide the required blanket functions. Models are developed to characterize and understand the governing heat transfer, thermal-hydraulic (including MHD), mass transfer processes (tritium behavior and possibly corrosion) and mechanisms degrading the tritium breeding, and to also help in extrapolating the small-scale test results to prototypical conditions.

# First-Stage Technology Readiness Levels for Blanket Subsystem

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4		Component and/or bench-scale validation in a laboratory environment.	Bench-scale validation of blanket concept through submodule testing in lab environment simulating heat fluxes or magnetic field over long times, and of mockups under neutron irradiation at representative levels and durations.
5	Proof of Principle	Component and/or breadboard validation in a relevant environment.	Integrated module testing of the blanket concept in: (1) an environment simulating the integration of heat loads and magnetic fields (if important for concept) at prototypical levels over long times; and (2) an environment simulating the integration of heat loads and neutron irradiation at prototypical levels over long times. Coupon irradiation testing of blanket structural material to end-of-life fluence.
6		System/subsystem model or prototype demonstration in relevant environment.	Integrated testing of the blanket concept subsystem in an environment simulating the integration of heat loads and neutron irradiation (and magnetic fields if important for concept) at prototypical levels over long times.



# Definitions of First Stage TRL's

## **TRL 4: *Component and/or bench scale validation in a laboratory environment***

Bench-scale submodule testing of blanket concept is performed in a laboratory environment simulating the heat load and/or magnetic field conditions in the absence of neutron irradiation at prototypical levels over long times (these need not be integrated). Progressive heat loads and/or magnetic fields are applied to a simple unit cell of the blanket concept that includes breeding material, structural material and coolant. The testing time should be long enough to overcome any transient effects. The operating conditions (temperature, pressure, flow rates, forces) should cover the expected prototypical conditions.

## **TRL 5: *Component and/or breadboard validation in a relevant environment***

Integrated module testing of the blanket concept in: (1) an environment simulating the integration of heat loads and magnetic fields (if important for concept) at prototypical levels over long times; and (2) an environment simulating the integration of heat loads and neutron irradiation at prototypical levels over extended times. The module should include the integration of a number of unit cells of the blanket concept. The testing time should be of the order of the expected operating lifetime. The operating conditions (temperature, pressure, flow rates, forces...) should cover the expected prototypical conditions.

## **TRL 6: *System prototype demonstration in an operational environment***

Integrated testing of the blanket concept subsystem in an environment simulating the integration of heat loads and neutron irradiation (and magnetic fields if important for concept) at prototypical levels over long times. The subsystem should include an integrated assembly of modules in a prototypical arrangement, including the integration of the subsystem to any cooled structural support. The testing time should be of the order of the expected operating lifetime. The operating conditions (temperature, pressure, flow rates, forces...) should cover the expected prototypical conditions.

# First-Stage Technology Readiness Levels for Blanket Subsystem

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7		System prototype demonstration in an operational environment	Prototypic blanket system demonstration in a fusion machine (for chosen confinement).
8	Proof of Performance	Actual system completed and qualified through test and demonstration	Actual blanket system demonstration and qualification in a fusion machine (for chosen confinement) over long operating times.
9		Actual system proven through successful mission operations	Actual blanket system operation to end-of-life in fusion power plant (DEMO) with operational conditions and all interfacing subsystems.



# Definitions of First Stage TRL's

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## ***TRL 7: System/subsystem model or prototype demonstration in relevant environment***

The blanket subsystem (consisting of an integrated assembly of modules) is tested in a fusion machine (for chosen confinement concept) and its operation demonstrated under prototypical conditions. The test unit should represent the complete blanket system as expected in a power plant, including connection to the heat recovery and tritium extraction systems.

## ***TRL 8: Actual system completed and qualified through test and demonstration***

The blanket subsystem is tested in the (chosen confinement) fusion machine (with at least full sector coverage and prototypical boundary conditions with adjacent sectors) and its operation demonstrated under prototypical conditions over long operating times. The test unit should represent the complete blanket system as expected in a power plant, including connection to the heat recovery and tritium extraction systems. The testing time should be of the order of the expected operating lifetime. Complementary qualification testing of the system in a fusion-like environment through a series of post end-of-life tests is performed to further qualify the component.

## ***TRL 9: Actual system proven through successful mission operations***

The blanket system is fully incorporated in a Demonstration fusion plant and its performance demonstrated to the end-of-life under fully prototypical conditions in a fully integrated mode with all system interfaces.



# Example TRL's Developed for Specific Blanket Concept Subsystem

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- **The DCLL blanket concept is chosen to illustrate the second-stage concept-specific TRL definition scheme**
  - A good compromise between the required attractiveness of a power plant and the necessary development program and risk.
  - On the pathway to a most attractive long-term blanket subsystem concept based on self-cooled lead-lithium blankets with  $\text{SiC}_f/\text{SiC}$  composites as structural material.
  - Other blanket concepts would have to be evaluated in a similar way in order to allow for an accurate and detailed assessment of their TRL's.
- **The DCLL concept is characterized by the following features:**
  - Eutectic lead lithium alloy Pb-17Li serving as breeder and coolant (self-cooled breeding zone).
  - He-cooled FW and blanket structure made of Reduced Activation Ferritic Steel (RAFS).
  - Flow channel inserts (FCI) made of  $\text{SiC}_f/\text{SiC}$  composite arranged between the flowing liquid metal and the steel duct walls, serving as electrical and thermal insulator.
  - Exit temperature of the liquid metal breeder/coolant  $\sim 700^\circ\text{C}$ , allowing the efficient use of a Brayton cycle power conversion system.



# Second-Stage Technology Readiness Levels for DCLL Blanket Concept Subsystem

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<b>Theme:</b>	<b>Harnessing Fusion Power</b>
<b>Subsystem:</b>	<b>DCLL Blanket Concept</b>

<b>T R L</b>	<b>Function</b>	<b>Generic Definition</b>	<b>Subsystem-Specific Definition</b>	<b>Example Facilities</b>
1		Basic principles observed and formulated.	System studies to define tradeoffs and requirements on blanket subsystem concept over reasonable range of power density, coolant temperatures, lifetime, and reliability. Requirements on flow channel inserts (FCI) for thermal and electrical insulations are formulated.	
2	Concept Development	Technology concepts and/or applications formulated.	Blanket concept geometries for FW cooling and self-cooled breeding zone proposed characterized, and candidate materials for FW/blanket structure and for FCI proposed. Requirements on the ancillary loops for heat and tritium extraction from the blanket formulated.	
3		Analytical and experimental demonstration of critical function and/or proof of concept.	Possibility to achieve tritium self-sufficiency demonstrated by 2-D neutronics analyses. Impact of the magnetic field on the liquid metal flowing in the large poloidal channels assessed with suitable MHD codes (flow distribution, velocity fields, pressure drops). He cooling of FW demonstrated with thermal-hydraulic and stress analyses. Basic material properties for structural material, FCI, and Pb-17Li experimentally characterized (without effect of irradiation) as required. Compatibility between key interfacing materials (RAFS/Pb-17Li and SiC/Pb-17Li) experimentally investigated. Solubility of tritium in Pb-17Li and possible extraction methods assessed. Principle methods to fabricate FW and blanket structure defined.	Lab-scale material facilities





# Definitions of Second Stage TRL's for DCLL Blanket Concept Subsystem

## **TRL 1: *Basic principles observed and formulated***

- Reasonable range of power density, coolant temperatures, lifetime, and reliability investigated by power plant studies.
- Requirements on flow channel inserts for thermal and electrical insulations are formulated.

## **TRL 2: *Technology concepts and/or applications formulated***

- Principal geometries for FW cooling and the self-cooled breeding zone investigated.
- Candidate materials for FW/blanket structure and for the flow channel inserts proposed.
- Requirements on the ancillary loops for heat and tritium extraction from the blanket formulated.

## **TRL 3: *Analytical and experimental demonstration of critical function and/or proof of concept***

- Possibility to achieve T self-sufficiency with the concept demonstrated by 2-D neutronics analyses.
- Impact of the magnetic field on the LM flowing in the large poloidal channels assessed with suitable MHD codes (flow distribution, velocity fields, pressure drops).
- Performance and limits of He-cooling of the FW demonstrated with T/H and stress analyses.
- Basic material properties for structural material, flow channel inserts, and lead-lithium breeder characterized and measured as needed (without effect of irradiation).
- Measurement of the thermal and electrical insulation properties of the candidate FCI material (representative coupons, measurements made perpendicular and parallel to the coupon surface).
- Compatibility between candidate struct. material (RAFS) and Pb-17Li investigated with loop tests.
- Compatibility between SiC flow channel inserts and Pb-17Li assessed with coupon tests in capsules.
- Solubility of tritium in Pb-17Li and possible extraction methods assessed.
- Principal methods to fabricate FW and blanket structure defined.

# Second-Stage Technology Readiness Levels for DCLL Blanket Concept Subsystem

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4		Component and/or bench-scale validation in a laboratory environment.	<p>Bench-scale submodules tested in separate effect test facilities.</p> <p>Liquid metal flow in strong magnetic field.</p> <p>Thermal-hydraulic, and mechanical tests of He-cooled FW mock-ups under high heat flux conditions.</p> <p>Compatibility tests with structural material and FCI-material in flowing Pb-17Li with representative conditions.</p> <p>Tritium extraction tests with candidate extraction method (permeator).</p> <p>Neutronics tests with dedicated mock-ups to validate calculated TBR.</p> <p>Impact of representative neutron irradiation on the properties of structural material and FCI (at least up to 10 dpa in steel, sufficiently high fluence of fast neutrons in fission reactor).</p>	<p>Bench-scale lab facilities (thermo-fluid, thermo-mechanical, MHD, material) with representative, heat loads, magnetic fields, flow rates and temperature levels</p> <p>Tritium lab facility</p> <p>Fission reactor/other relevant neutron source with sufficiently high fluence</p>
5	Proof of Principle	Component and/or breadboard validation in a relevant environment.	<p>Integrated testing over extended times of a representative blanket submodule, simulating the blanket conditions in regard to neutron irradiation, magnetic field, heat loads, and temperature levels.</p> <p>Coupon irradiation tests of the materials for blanket/FW structure and FCI's performed in a fusion relevant neutron field up to the end-of-life fluence in DEMO blankets.</p>	<p>ITER</p> <p>IFMIF</p>
6		System/subsystem model or prototype demonstration in relevant environment.	<p>Testing of a blanket subsystem module (including a number of unit cells of the concept geometry) with the required ancillary systems for heat and tritium extraction in a fusion environment. The environment should be typical for the conditions in a DEMO plant in regard to magnetic field strength and gradients, the neutron energy spectrum, the heat loads, the temperature level in all elements of the module, and the vacuum condition in the plasma chamber.</p>	<p>ITER Upgrade?</p> <p>Or early CTF</p>



# Definitions of Second Stage TRL's for DCLL Blanket Concept Subsystem

## **TRL 4: *Component and/or bench scale validation in a laboratory environment***

- Bench-scale tests of sub-modules (representative of unit cell of concept) in separate-effect facilities:
  - Liquid metal flow in strong magnetic field.
  - T/H and mechanical tests of He-cooled FW mock-ups under high heat flux conditions.
  - Compatibility tests with structural material and FCI-material in Pb-17Li flowing with representative conditions (V, T, dT in flow direction, magnetic field).
  - Tritium extraction tests with candidate extraction method (permeator).
- Neutronics tests with dedicated mock-ups (blanket typical volume composition, representative neutron energy spectrum) to validate calculated TBR.
- Impact of representative neutron irradiation on the properties of structural material and FCI (at least up to 10 dpa in steel, with sufficiently high fluence of fast neutrons in fission reactor).

## **TRL 5: *Component and/or breadboard validation in a relevant environment***

- Integrated testing over extended times of a representative blanket sub-module (including at least a complete unit cell of the concept geometry) simulating the blanket conditions in regard to neutron irradiation, magnetic field, heat loads, and temperature levels.
- Coupon irradiation tests of the materials for blanket/FW structure and FCI's performed in a fusion relevant neutron field up to the end-of-life fluence in DEMO blankets.

## **TRL 6: *System prototype demonstration in an operational environment***

- Testing over extended times of a blanket subsystem module (including a number of unit cells of the concept geometry) with the required ancillary systems for heat and tritium extraction in a fusion environment. The environment should be typical for the conditions in a DEMO plant in regard to magnetic field strength and gradients, the neutron energy spectrum, the heat loads, the temperature level in all elements of the module, and the vacuum condition in the plasma chamber.

# Second-Stage Technology Readiness Levels for DCLL Blanket Concept Subsystem

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7		System prototype demonstration in an operational environment	<p>A prototype of a blanket subsystem assembly (including a number of modules) with the required ancillary systems is demonstrated in a fusion machine with relevant boundary conditions and at relevant power level and coolant conditions and up to the fluence anticipated for DEMO.</p> <p>The tritium breeding rate is measured and compared with analytical predictions; on-line TBR by varying the Li-6 concentration is demonstrated.</p> <p>The effectiveness of the permeator tritium extraction system is demonstrated.</p> <p>The build-up of activated impurities in the primary Pb-17Li loop is monitored and compared with predictions.</p> <p>The exchange of the module is demonstrated.</p> <p>Pressurization tests with the irradiated module up to the full helium operating pressure are performed to demonstrate that it can survive likely accident conditions without losing its integrity.</p> <p>The FCI integrity and the degree of material losses/depositions through the flowing Pb-17Li are investigated by destructive testing of the replaced blanket module.</p>	CTF-like with full subsystem testing + ancillary equipment and diagnostics
8	Proof of Performance	Actual system completed and qualified through test and demonstration	System demonstration of a large blanket assembly (consisting of a number of blanket modules covering a large sector of the fusion machine) and of its ancillary equipment through long-term testing in a fusion machine at a power level and temperatures at least as high as anticipated in the DEMO power plant and a neutron fluence equal to the anticipated end-of-life fluence in DEMO ("Reliability growth testing").	CTF-like to end of life fluence
9		Actual system proven through successful mission operations	Actual blanket system operation to end-of-life in fusion power plant (DEMO) with prototypical conditions and all interfacing subsystems. Demonstration of tritium self-sufficiency, efficient power production and tritium control, anticipated blanket reliability and lifetime, and required	DEMO



### ***TRL 7: System/subsystem model or prototype demonstration in relevant environment***

- A prototype of a blanket subsystem assembly (including several modules) with the required ancillary systems is tested in a fusion machine (for the chosen confinement concept) with relevant boundary conditions at power levels and coolant conditions typical of DEMO and moderate fluences.
- The TBR is measured and compared with the results of predictive neutronics calculations.
- On-line adjustment of the TBR by varying the Li-6 concentration in the Pb-17Li is demonstrated.
- The effectiveness of the permeator tritium extraction system is demonstrated, and the resulting T partial pres. in the primary Pb-17Li loop is measured in order to confirm the anticipated T control.
- The build-up of activated impurities (corrosion products, polonium) in the primary Pb-17Li loop is monitored and compared with predictions.
- The exchange of the module (at the end of its lifetime or in case of failure) is demonstrated.
- Pressurization tests with the irradiated module up to the full He operating pressure are performed to demonstrate that it can survive anticipated accident scenarios (such as an internal LOCA) without losing its integrity (no LM leak, no large deformations affecting replacement procedures).
- The FCI integrity and the degree of material losses/depositions by the interactions between the flowing Pb-17Li, the blanket structure, and the FCI's are investigated by destructive testing of the replaced blanket module.

### ***TRL 8: Actual system completed and qualified through test and demonstration***


- System demonstration of a large blanket assembly (consisting of a number of blanket modules covering a large sector of the fusion machine) with its ancillary equipment through long-term testing in a fusion machine (for the chosen confinement concept) at a power level and temperatures at least as high as anticipated in DEMO and a neutron fluence equal to the anticipated end-of-life fluence in DEMO (reliability growth testing).

### ***TRL 9: Actual system proven through successful mission operations***

- Actual blanket system operation to end-of-life in fusion power plant (DEMO) with prototypical conditions and all interfacing subsystems.
- Demonstration of tritium self-sufficiency, efficient power production and tritium control, anticipated blanket reliability and lifetime, and required blanket replacement time provided by successful operation of the complete blanket subsystem.

# Future Effort

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- **Need to converge on document for development of TRL's for example cases (power extraction/conversion system and blanket subsystem).**
  - Will use all feedback from this meeting
  - Need additional feedback soon
  - Report ready by December 2008?
  - FESAC meeting?
- **How to best couple this work to the information in our interim report?**
- **Need better definitions of other subsystems under FESAC Theme C**
- **Need to develop TRL's for all subsystems under Power Extraction/Conversion and then Tritium Fuel Cycle**
- **Need help from experts**
- **Full report in 2009?**
-  **Other publications/presentations ?**