

Effective Power Management in DEMO, Work necessary to **prove feasibility and to **increase attractiveness****

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Areas addressed:

- Power density in the power core
- First wall
- Breeding blankets
- Divertor target plates
- Ancillary systems for heat and tritium extraction
- Power Conversion system

A) Power density in the core

Power density limited by the **maximum allowable** values of NWL, FW surface heat flux, and divertor heat load.

Size of the power core determined by **the average NWL**.

However, *lifetime, replacement frequency, fabrication cost and amount of waste* to be reprocessed from blanket and divertor during lifetime of the plant determined by **maximum NWL**.

Therefore, in order to minimize COE,

- **Minimize peaking factors for NWL, FW surface heat flux , and divertor surface heat flux**

B) First wall

Maximum allowable **surface heat flux at FW** usually limited by

- thermal stresses
- maximum allowable temperature of the structure
- maximum allowable interface temperature to the coolant

Development goals:

Minimize ratio between pumping power and cooling efficiency (gas cooling) by

- adjusting local coolant velocity to local cooling needs,
- **optimize heat transfer by employing artificial surface roughness**
- **increase allowable surface temperature by plating RAFS with ODS-steel**

Special issue to be investigated in connection with plasma physics:

- **protection of the first wall**

C) Breeding blankets

Each class of **breeding blanket concepts** has its own advantages, disadvantages, limitations, and development needs.

Main differences between these concepts are:

Ceramic breeder blankets require a lot of Beryllium as neutron multiplier (at least 4 times the volume of the breeder), have limited performance in terms of allowable power density and achievable efficiency (coolant exit temperature, pumping power), and need a complicated structure (many cooling plates/tubes inside the blanket module).

Main crucial issue: Need to **control TBR in situ** with a precision better 1 %, no practicable solution know.

Blankets based on RAFS-structure have He-exit temperature < 500 C, resulting in net efficiencies < 40 %, and do not enable the use of BRAYTON cycle power conversion system (RANKINE cycle has potential for steam/beryllium chemical reaction).

Molten salt blankets require a high temperature structural material (melting point of FLiBe is 459 C!), have severe limitations in the heat transfer (low conductivity, high viscosity), extremely low T-solubility (difficult T-control), and need a difficult chemistry to control the aggressive TF.

Altogether the ratio

potential for attractive power plants/ required development and risk,
is rather limited.

Self-cooled liquid metal breeder blankets require either electrical insulation between breeder and structure to overcome MHD issues (insulating coatings, flow channel inserts), or require SiC-composites as structural material. They offer the simplest design (no internal cooling surfaces required) and the possibility to achieve an exit temperature 100 – 200 K higher than the maximum structure temperature. The possibility to adjust the Li-6 concentration enables efficient on-line TBR-control. Since the long development of insulating coatings has not been successful, the main candidate concept is the lead-lithium blanket with SiC-composite structure (SCLL blanket), offering efficiencies up to 60 %. Therefore, this concept is the only self-cooled blanket assessed in the followings.

Dual coolant lead-lithium blankets, based on RAFS structure and SiC- flow channel inserts serving as electrical and thermal insulator require a limited extrapolation of present day technology and allow coolant exit temperatures up to ~ 700 C, enabling the use of BRAYTON cycle power conversion system with efficiencies up to 45 %. They are already suitable for attractive power plants, but in addition they are on the pathway to the very advanced SCLL blanket.

In the followings, the main crucial issues of these two blanket concepts are described.

Main issues of the DCLL blanket module

a) *Impact of the magnetic field on the liquid metal flow*

MHD Pressure drop minimized by electrically insulating FCI's, but influence of magnetic field on velocity fields and flow distribution still important. **More modeling and experimental MHD work necessary to**

- **minimize heat losses from LM to He,**
- **keep thermal stresses in the FCI's < given limits,**
- **maintain material losses steel->LM below allowable values.**

b) *Development and long term behavior of SiC-FCI's*

FCI's require SiC-composite with low thermal and electrical conductivity perpendicular to plate. Different from requirement for FW application. Dedicated development necessary to achieve a material with

- **minimized thermal conductivity (< 2 W/m*K),**
- **allowable delta T > 200 K across wall without getting damaged by thermal stresses,**
- **sealing layers at all surfaces /closed pores near the surfaces in order to avoid "soaking in" of LM**
- **life time under neutron irradiation equal to life time of structural material**

c) *Fabrication technology of RAFS structure*

- Fabrication of panels with parallel cooling channels as needed for FW box and stiffening plate difficult. More work required to qualify HIP methods for this process. (Fracture toughness of diffusion welds!)

- **Complicated PWHT required after the "last weld" is made.**
- **"Sliding seals" are required for concentric coolant access pipes**

Main issues of the SCLL blanket modules or segments

Largest challenge for the development of this concept is the feasibility to develop a SiC-composite having after high fluence neutron irradiation

- **Sufficiently high thermal conductivity ($> 15 \text{ W/m}^{\circ}\text{K}$)**
- **Sufficiently high strength especially against thermal stresses,**
- **sealing layers at all surfaces /closed pores near the surfaces in order to avoid “soaking in” of LM**
- **the possibility to make all the high quality joints necessary to assemble a segment from individual elements**

Since the development of a suitable composite requires a large R&D program, and especially high fluence irradiation tests, it will probably not be possible to develop the SCLL blanket concept for a first DEMO plant.

However, many issues of the SCLL concept are already dealt with in the development of the DCLL concept, i.e. in the areas of ancillary systems for heat and tritium extraction including tritium control and the power conversion system.

Therefore, it is fair to say that the DCLL concept is on the pathway to the more advanced, really attractive SCLL blanket concept.

D) Divertor target plates

The alpha-particles produced by the fusion reaction have to be stopped either by the FW covering the blankets, or by specially designed high heat flux plates. The design of such “divertor target plates” is a very challenging task. The main requirements are:

- a) Capable of taking a surface heat flux in the order of 10 MW/m²,**
- b) Lifetime of the target plates should not be shorter than the lifetime of the blanket modules in order to avoid additional down time for replacing them.**
- c) Allowing a surface erosion of up to 5 mm during the lifetime of the plate.**
- d) The heat input into the plates has to be used effectively in the power conversion system**
- e) The operating temperature of the plates must be higher than the embrittlement temperature of the plate structure. For this reason, the coolant temperature must be > 600 C, making helium to the main choice for coolant candidate.**
- f) The required pumping power for the plate coolant must be < 10 % of the heat extracted from the plate.**
- g) It must be possible to align the target plates precisely relative to the plasma with a tolerance < 1mm.**

Possible candidate designs of divertor targets:

- **helium coolant at 10 Mpa pressure and temperatures in the range 600-800 C**
- **tungsten-alloys as structural material and for erosion-tiles**
- **geometry: plate, T-tube, or modular fingers**

Maximum heat flux of 10 MW/m² is feasible with all three geometries.

***Thermal stresses decrease in the direction
Plate -> T-tube -> Fingers***

However, complexity and number of elements increase in the same direction.

Example:

Total number of elements needed for one plant:

500 plates; 50,000 T-tubes; 250,000 finger-modules

Main challenges in the development of divertor target plates:

- **development of suitable tungsten alloys with sufficiently large temperature window (embrittlement, recrystallization)**
- **transition from tungsten target to steel manifold (differential thermal expansion)**
- **sufficiently high reliability in spite of the large number of elements.**

E) Ancillary systems for heat and tritium extraction, shown for the DCLL blanket

The following ancillary systems will be necessary:

- a) Primary lead-lithium loop for heat extraction from self-cooled breeding zone,**
- b) Primary helium loop for heat extraction from FW and blanket structure,**
- c) Primary helium loop for heat extraction from divertor target plates**

All three loops deliver their heat to the helium loop of the BRAYTON cycle power conversion system via separate heat exchangers.

There are purification and detritiation systems required in all three loops, but the main tritium extraction system has to be installed in the primary lead-lithium loop.

Two main crucial issues:

- What is a suitable material for the HX tubes between lead-lithium (700 C, 2 MPa) and the secondary helium (700 C, > 10 MPa) ?**
- Which tritium extraction method is suitable for this blanket concept?**

Candidate materials for the tubes of the intermediate HX

Under discussion:

- a) Ni-based alloy with protective coating
- b) Refractory metals (Nb, Ta, V-alloys)
- c) SiC-composites

Reference solution in present studies are refractory metals. Their feasibility, however, depends mainly on two requirements:

1. **Very low tritium partial pressure on both sides of the tube to avoid too large a tritium inventory,**
2. **Impurity level on both sides of the tubes extremely low (O, N, C) to avoid embrittlement.**

To meet the *first requirement*, the tritium extraction system must maintain a partial pressure < 1 Pa. Performance of bubble towers as suggested for HCLL blankets is limited to partial pressures > 50 Pa

Requirement 2 is a challenge for the operation of the BRAYTON power conversion system.

Thinkable solution is to avoid any potential for impurity ingress during operation (helium pressure $>$ surrounding pressure), and to clean-up the helium loop with getters prior to rising the temperature in the HX to operating conditions.

Tritium extraction method from Pb-17 Li

It is anticipated to arrange in the main stream of the primary lead-lithium loop bundles of tubes made of a refractory metal (Nb, Ta, V-alloys) serving as permeation window between the Pb-17 Li flowing inside these tubes and a vacuum chamber surrounding the tube bundles. The intention is to maintain with such a permeator the tritium partial pressure in the lead-lithium at a value < 1 Pa in order to minimize tritium losses to the surroundings and the tritium inventory in the entire plant.

Main challenges for the development of such a permeator are:

- **Determination of the tritium mass transfer from the turbulent flowing lead-lithium through the laminar sub-layer to the inner surface of the tubes,**
- **Permeation of T-atoms through the tube wall,**
- **Recombination of the T-atoms to T₂-molecules at the outer tube surfaces in the vacuum chamber,**
- **Impact of impurities on the achievable T-partial pressure**
- **Exclude any potential for ingress of impurities to the permeator tubes.**
- **Study material transport in a lead-lithium loop with thermal gradients and with the liquid metal in contact with the RAFS and the SiC in the blanket and primary loop, and with the materials in permeator and intermediate HX**

F) Power Conversion system

The BRAYTON cycle power conversion system has the advantage that any potential for chemical reactions between high pressure steam and the chemical reactive materials in the blanket is eliminated. Furthermore, net efficiencies $> 50\%$ for coolant temperatures $> 800\text{ C}$ are feasible only with a BRAYTON cycle system.

Self-cooled lead-lithium blankets with a SiC-composite as structural material have the potential for LM exit temperatures $> 1000\text{ C}$, promising a thermal efficiency of $> 55\%$.

For the Dual Coolant Lead Lithium Blanket LM exit temperatures up to $\sim 800\text{ C}$ are envisaged, leading to efficiencies up to 50% .

Large BRAYTON cycle components as needed for a fusion power plant **need considerable extrapolation** from the present status of development. Especially demanding are the required **recuperators**, where both key parameters, the required **pressure drop** and the achievable **delta T**, have to be **minimized** at the same time.

Fortunately, the large closed cycle helium turbines as under development for high temperature fission reactors are in general smaller and cheaper than comparable steam turbines.

Conclusions

From the present point of view, a DEMO plant should (and could) be build based on the following concepts:

- Dual Coolant Lead Lithium blanket with helium-cooled reduced activation ferritic steel for FW and blanket structure, and flow channel inserts made of SiC-composites,**
- Helium cooled divertor target plates based on tungsten alloy structure,**
- Brayton cycle power conversion system with closed cycle helium turbines,**
- Refractory alloy (Nb, Ta, or V) permeator in the primary lead lithium loop for tritium extraction down to a partial pressure < 1 Pa**

The DCLL concept is already a good compromise between the required extrapolation of present day technology, and the desired DEMO performance. In addition to this, it has the potential for a really attractive later power plant because it is on the pathway to an advanced power plant with self-cooled lead lithium blankets based on SiC-composite as structural material.

Key issues to be solved before such a DEMO can be designed are:

- **Development and qualification of a SiC-composite suitable for flow channel inserts,**
- **MHD modeling and testing for the flow in the DCLL blanket including natural convection and heat transfer,**
- **Fabrication technology for blanket steel-structure.**
- **Development and qualification of a permeator tritium extraction system,**
- **Development and qualification of a tungsten alloy for the divertor target plates with a sufficiently large temperature window between embrittlement at the low side and recrystallization at the upper side,**
- **Development and qualification of the main components (Recuperator, turbines, compressors, heat sink) of a BRAYTON cycle power conversion system, taking benefits from the development of high temperature fission reactors.**