GROWING SYNERGIES BETWEEN FISSION AND FUSION RESEARCH TOWARDS DEMONSTRATION PLANTS

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Deuterium can be extracted from natural water: Standard mean ocean water contains 0.016% D

Tritium must be bred internally from lithium
- ~150 kg tritium is required per GWe year of fusion power
- About 100 g tritium is produced per year in a standard CANDU reactor
- Breeding reactions in a fusion reactor
  \[ n + ^6\text{Li} \rightarrow ^3\text{He} + ^4\text{He} \]
  \[ n + ^7\text{Li} \rightarrow ^3\text{He} + ^4\text{He} + n \]
SYNERGIES BETWEEN FISSION AND FUSION ENERGY

1 – Design methods and codes for plasma facing components and tritium breeding blankets (structural materials, manufacturing, reliability, lifetime…)

2 – Safety approach & licensing (safety regulation, licensing procedure…)

3 – Materials & Systems Technology (high temperature, neutron damage): AFMA, ODS, C-C, SiC₆-SiC… and design rules

4 – In service inspection, decommissioning & waste management

5 – Tritium breeding & Production of initial load
IN-VESSEL COMPONENTS & BREEDING BLANKETS

Very severe operating conditions & requirements

- High surface heat flux
  0.5 (FW) ➞ 15 MW/m² (divertor)

- High neutron wall loading (FW)
  ~2.5 MW/m², ~150 dpa (Fe)

- Operation under void (plasma), complex torus geometry
  ➞ Low coolant leakages

- High magnetic field (~7 Tesla)
  (high MHD effects)

Moreover: Remote access in high radiation field
(maintenance, inspection, repairs, diagnostics,...)

(Source CEA, JF. Salavy, Nov 2006)
Thermo-mechanical Analysis of HCLL Blanket Module (CAST3M)

Simulation of LOCA on the WCLL primary cooling system (CATHARE + COPERNIC)

Evaluation of Tritium Breeding Ratio (TBR) with TRIPOLI-4

H₂ release from cryogenic systems, Loss of Vacuum Accident (CAST3M/TONUS)
Analysis with CASTEM of thermal and mechanical loading of ITER-TBM (HCLL concept) in LOCA conditions

Standard CAST3M with implementation of specific materials properties (Be, Pb-Li, helium)
Specific aspects of D-T Fusion Tokamak reactors
- Inherent safety of plasmas
- Production of radioactive nuclei by activation only
- Low decay heat
- Pulsed operation & Control of plasma disruption
- Large energy stored in the magnetic configuration

Common features with fission reactors
- Confinement of radioactive materials: large Tritium hold-up, activation products in the system (Mn, Fe, Co, Ni, Mo in steels + Cu, Co, Zn in copper alloys)
- Removal of power (in operation and at shutdown)

Safety and licensing
- Adaptation of Fission safety demonstration to Fusion experimental devices → Safety case of ITER and DEMO
### Present Generation

<table>
<thead>
<tr>
<th>Fission (Gen. II&amp;III)</th>
<th>Fusion (ITER)</th>
<th>Fission (Gen. IV)</th>
<th>Fusion (Reactor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$ (structural material)</td>
<td>$&lt;300^\circ\text{C}$</td>
<td>$&lt;300^\circ\text{C}$</td>
<td>500-1000$^\circ\text{C}$</td>
</tr>
<tr>
<td>DPA max (internal components)</td>
<td>$\sim 1$ dpa</td>
<td>$\sim 3$ dpa (TBM)</td>
<td>$\sim 30$-$100$ dpa</td>
</tr>
<tr>
<td>He Production</td>
<td>$\sim 0.1$ appm</td>
<td>$\sim 30$ appm</td>
<td>$\sim 3$-$10$ appm</td>
</tr>
<tr>
<td>He/dpa</td>
<td>$\sim 0.1$</td>
<td>$\sim 10$</td>
<td>$\sim 0.1$</td>
</tr>
<tr>
<td>Structural material</td>
<td>Austenitic steels, Zircaloy</td>
<td>Austenitic steels</td>
<td>Ferritic steels, Superalloys ? SiC-SiC ?</td>
</tr>
</tbody>
</table>

### Next Generation

**Comparable service conditions:** *High temp.* ($>500^\circ\text{C}$) & *High dpa* ($>100$ dpa)
Options considered

➢ Low activation martensitic steel
  ➢ Replace elements subject to activation
    Ni, Mo… → Mn, W…
  ➢ Low activation martensitic steel EUROFER
    • Operating conditions 500-650°C (ODS)
    • Several tonnes already manufactured

➢ Vanadium alloys or SiC composite ceramics
  ➢ Heat resisting materials with fast des-activation
  ➢ Less known materials → Longer term use
    • Operating conditions
      • 700°C (V)
      • 1000°C (SiC-SiC)
COMPOSITE MATERIALS FOR INTERNALS: CONTROL RODS

C/C & SiCf/SiC composites

→ **Manufacturing:** 2D & 3D woven fibres (C, Hi-Nicalon S), interphases, CVI or pitch densification, anti-oxidation coating (Si, B)...
→ **Technical file for codification** of design Standards

**Fuel Pin Clading**

**Nite Process**

**Kyoto University**

**Hexagonal wrapper tube**

**for SFR subassembly**

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**Deformation of Triplex composite fuel cladding (CEA)**

*ORNL (L. Snead)*
MATERIALS CONSIDERED FOR FUSION REACTORS

**Breeding Blankets (DEMO ➔ Reactor)**

- **Structural materials:** EUROFER, EUROFER ODS, SiC/SiC (+ beyond EU: other M/FS, V alloys)
- **Tritium breeder materials:** LiPb$_{eu}$, Li$_2$TiO$_2$, Li$_4$SiO$_4$ (+ beyond EU: Li$_2$O, Li)
- **Functional materials:** Be (neutron multiplier), permeation barrier & corrosion, electric insulators in SiC/SiC, shielding PP (W)
- **Coolants:** He, LiPb$_{eu}$ (+ beyond EU: Li, water SP)

**Divertor (DEMO ➔ Reactor)**

- **Structural materials:** W alloys, Eurofer (+ interface in C), Eurofer ODS, SiC/SiC (+ brazing?) (+ beyond EU: other M/FS, V alloys)
- **Shielding materials:** Ceramics or W tiles
- **Coolants:** He, pressurized water, LiPb$_{eu}$ (+ beyond EU: Li)

**R&D needs (measurements & improvements)**

- Behaviour under irradiation (mechanical, thermal, neutronic, electrical, …)
- Irradiation behaviour
- Modelling
- Compatibility between materials
- Fabrication (ex.: CIC, particle bed..)
- Assembly (ex.: interface, weldings…)
- Low long term activation
Typical Tokamak Configuration
T-Breeding Blanket: Dual Coolant Lithium Lead

<table>
<thead>
<tr>
<th>Fusion Power Reactor</th>
<th>Dual-Coolant T-Blanket</th>
</tr>
</thead>
<tbody>
<tr>
<td>He, 80 bars</td>
<td>Pb-17Li, ~bar</td>
</tr>
<tr>
<td>300, 480 °C</td>
<td>480-700 °C</td>
</tr>
</tbody>
</table>

Dual-Coolant T-Blanket

Martensitic Steels (550 °C)
ODS Ferritic steels (700 °C)
SiC-SiC th. & elect. insulator

F W: T max= 625 °C
Channel: Tmax= 500 °C
Insert: Tmax~1000 °C
HCLL

He: $T_{\text{in (FW)}} / T_{\text{out (breeder)}}: 300/500°C \ P=8\text{MPa}$

LiPb: $T_{\text{in (FW)}} / T_{\text{out (breeder)}}: 370/660°C$

EUROFER: $T_{\text{max}} = 520°C$ (FW)

TBR: 1.22 ($^6\text{Li}: 90\%$)

Thermal efficiency: $>35\%$
Fabrication of He Cooling Plate and Stiffeners for HCLL TBM

Manufacturing technology (CEA patent)

Before welding

After laser welding

He cooled heat exchanger for FUSION

CEA/DEN/DM2S

DIADEMO mockup for SFR of sodium/gaz heat exchanger

After HIP cycle

After HIP (homogeneous μ-structure)

After straightening, HIP and machining

FISA 2019 / EURADWASTE ’19 - 4-7 June, 2019 Pitesti, Romania
RCC-MR, developed for Sodium Cooled Fast Reactors in Europe (EFR, Phenix lifetime extension), has been selected for the design & construction of ITER Vacuum Vessel (high temperature and low pressure operation, “box” structure, 316 L(N) steel, fabrication, weldings…)

Huge R&D at European level to develop and characterize Eurofer steel

Introduction of Eurofer97 in the French RCC-MRx design and construction code

RCC-MRx is selected for the design and construction of the test blanket module (TBM) for ITER. The code will continue to be developed within the framework of the TBM program for fusion relevant aspects
Control of Phenix Core Supporting Structure Weldings

- Ultrasonic sensors
- X-Tomography
Gen-IV Fission & Fusion Reactors: A High Level of Integration

- Iter is a major step for fusion
- Iter = integration of both present fusion and nuclear constraints

New engineering tools

Integration studies of Iter IR diagnostic in equatorial port plug no. 1

InfraRed endoscope in Tore Supra

2 m

20 m
CEA robotic developments of long reach arm for **hot cells inspection**

(1kg payload capacity, 6 segments 11 axis, L=7.2m, atmospheric pressure, ambient T°)

CEA development for **Tokamak in-situ inspection** : Articulated Inspection Arm (AIA)

(10 kg payload, 9.5 meters total length, Ultra High Vacuum (10^-6 Pa) and 120°C)

AIA is a versatile arm able to plug different tools (camera, leak detection, diagnostics...)

Mock-up of arm for hot cells inspection
First wall monitoring in fusion devices

- Temperature measurement by Infra-Red camera
- Measurement of erosion by confocal microscopy

In-situ IR monitoring during plasma shot in fusion device

Infra-Red camera for temperature monitoring

Bi-chromatic IR camera for steam generator tube temperature monitoring to detect abnormal conditions
- Virtual Reality for dismantling fission reactors & Fuel cycle plants

Dismantling scenario qualification (CEA/Marcoule)

Accessibility studies for in situ manufacturing (CEA/WEST project)

Close collaboration between Fusion and Fission teams for the development of Virtual Reality instruments
Laser Induced Breakdown Spectroscopy (LIBS) developed for real-time analyses (sample composition) in severe environment.

Laser induced breakdown spectroscopy application in Joint European Torus (JET) 

Development of LIBS (ps) for both quantitative detection (composition and profilometry) of tritium retention in Tokamak.
ITER & MAGNETIC FUSION DEVELOPMENT PATHWAY

<table>
<thead>
<tr>
<th>Thermal Power</th>
<th>kWth</th>
<th>1000</th>
<th>100</th>
<th>10</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET</td>
<td></td>
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<tr>
<td>Power Plasma</td>
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<tr>
<td>Robotics, Tritium technology…</td>
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<tr>
<td>ITER</td>
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<tr>
<td>DEMO: Reliability &amp; Economic Performance (Materials + T-Blanket)</td>
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<td>Long pulse plasma + supraconductor, self-cooled plasma facing components, heating devices, diagnostics…</td>
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Tritium g  kg  10s kg

Pulse length (s)

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TRANSAT, a European H2020 project focused on Fission-Fusion commonalities on tritium (CEA as coordinator, 8 EU countries involved, 2018-2021)

Cross-cutting support to improved knowledge on tritium management in fission and fusion facilities

1. Tritium permeation control
2. Assessment of the tritium inventory using state-of-the-art modelling tools
3. Engineering solutions for detritiation techniques and waste management
4. Refinement of the knowledge on outgassing, radiotoxicity, radioecology, radiobiology, dosimetry and metrology of tritium

First International School on Tritium organised in Ljubljana (Slovenia, 25-28/03/2019)
SYNERGIES BETWEEN FISSION AND FUSION NUCLEAR ENERGY

Summary

➢ Nuclear Design and Technology
  ▪ Codes and design methods
  ▪ High temperature and neutron resistant materials
  ▪ Gas, water or liquid metal cooled systems technology
  ▪ In service inspection, maintenance in hostile environment
  ▪ Dismantling and waste management

➢ Safety approach and licensing

➢ Increased synergies for the Fusion DEMO reactor
  ▪ Optimization of blanket design for energy and tritium production
  ▪ Demonstration of full tritium breeding and recovery
  ▪ Production of initial tritium load

➢ Education in nuclear physics and engineering
  ▪ Attraction of young scientists in the fields of nuclear energy
  ▪ Stimulation of education and training in nuclear physics and engineering

➢ Towards more integrated Fusion and Fission programs