Neutronic Activation Analysis for ITER Fusion Reactor

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100° Congresso Nazionale SIF
Outlook

- Nuclear Fusion
- International Thermonuclear Experimental Reactor (ITER)
- Neutronics Computational Tools
- Activation Analysis for ITER Reactor
Nuclear Fusion

D + T → ⁴He (3.5 MeV) + n (14.1 MeV)

Q=17.6 MeV

How much energy from...

1 g (²H,³H) → 7*10⁸ KJ
1 g ²³⁵U → 8*10⁷ KJ
1 g petrol → 40 KJ
1 g coal → 0.04 KJ
Fuel Availability on the Earth

DEUTERIUM: natural abundance 0.0154 % of H → reserve in the oceans $2 \times 10^{16}$ Kg

TRITIUM: β radioactive with 12 years half life, not available in large quantities

What is available?

LITHIUM: from 1 kg of Lithium can be produced 0.43 kg of tritium

Lithium reserve in Earth crust $[1] \rightarrow 1.3 \times 10^9$ Kg, TRITIUM: $5.6 \times 10^8$ Kg

Lithium reserve in the ocean $[1] \rightarrow 2.3 \times 10^{14}$ Kg TRITIUM: $10^{14}$ Kg

1 kg of D-T fuel produces $7 \times 10^8$ MJ ≈ 200 GWh

Year World Energy Consumption: 145 Gwh$[2]$

Fusion could fulfil energy supply for 1.5 billion years

How to Achieve Fusion

Inertial Confinement

- Iced DT pellet as a fuel
- Heating trough laser compression
- Works in pulse mode only

Magnetic Confinement

- At temperature required for fusion to occur, plasma is completely ionized
- Charge particles can be confined using magnetic field
- Application of this concept are the Tokamak (like ITER)
The plasma is a secondary winding of a transformer. The resultant toroidal plasma current provides for Ohmic heating and generates the poloidal magnetic field $B_\theta$. Poloidal coils generated an additional toroidal magnetic field $B_\phi$ for greater stability.
Economy of a Tokamak

Ignition: fusion charge products compensate for energy loss ($\alpha$ in the case of DT plasma).

Break-even: Fusion energy released must exceed the energy supplied.

$$\frac{E_{FU}}{\eta_{IN} E_{IN}} = Q_p = 1$$
Where we are now?

ITER parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maior radius</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>2 m</td>
</tr>
<tr>
<td>Volume</td>
<td>830 m³</td>
</tr>
<tr>
<td>Plasma current</td>
<td>15 MA</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>5.3 T</td>
</tr>
<tr>
<td>Density</td>
<td>$10^{20}$ m⁻³</td>
</tr>
<tr>
<td>Peak Temperature</td>
<td>$2 \times 10^8$ K</td>
</tr>
<tr>
<td>Fusion Power</td>
<td>500 MW</td>
</tr>
<tr>
<td>Plasma Burn</td>
<td>300-500 s</td>
</tr>
</tbody>
</table>
ITER Project

ITER SITE: Cadarache (France)

TER TIMELINE:
2008: Site levelling
2010: Start Tokamak complex excavation
2013: Start Tokamak complex construction
2014: Arrival of first manufactured components
2015: Begin tokamak assembly
2019: Complete tokamak assembly
2020: First Plasma
2027: First D-T Operation

MAIN GOAL: Q>10
500 MW of fusion power from 50 MW input power
ITER Machine

- Height: 30 m
- Diameter: 28 m
ITER Machine

VACUUM VESSEL

30 m

28 m
ITER Machine

VACUUM VESSEL

BLANKET

30 m

28 m
ITER Machine

VACUUM VESSEL

BLANKET 30 m

DIVERTOR

28 m

POLOIDAL FIELD COILS

TOROIDAL FIELD COILS
ITER Machine

- VACUUM VESSEL
- BLANKET
- DIVERTOR
- POLOIDAL FIELD COILS
- TOROIDAL FIELD COILS
- CENTRAL SOLENOID
ITER Machine

VACUUM VESSEL

44 openings (“ports”):
- 18 upper ports
- 17 equatorials ports
- 9 lower ports
Neutronics in Fusion Technology

DT Fusion Reaction

\[ Q_{\text{DT}} = 17.6 \text{ MeV} \]
\[ P_{\text{FUSION}} = 500 \text{ MW} \]
\[ \Phi_n = 10^{14} \text{ n/cm}^2\text{s} \]
on the First Wall

- **Neutrons:**
  - Induce radioactivity in the structural materials as well as in the coolant.
  - Damage materials through atom displacement, affecting mechanical and electric properties.
  - Produce hydrogen and helium, which make welding difficult if > 1 appm.
  - Heat superconducting coils reducing their effectiveness.

**These effects must be studied!**
The safety on a fusion plant requires a deep knowledge of the radiation map due to:
- “prompt” neutron and $\gamma$
- $\gamma$ produced by activated material, in particular after the shutdown, when maintenance is planned.

Three step procedure:

- Monte Carlo calculation of the spectral neutron flux in the materials
- Deterministic calculation of the radioactivity induced by neutrons as a function of irradiation or decay time
- Monte Carlo $\gamma$ transport and calculation of the dose rate in the region of interest
Rigorous 2 Steps (R2S) Method

1) Monte Carlo neutron transport
2) Deterministic activation calculation
3) Monte Carlo $\gamma$ transport

INPUT

- MCNP Input File
  (3D geometry, materials, cross section libraries, neutron source)

CODE

MCNP5 - N

OUTPUT

Neutron flux and spectra map
Rigorous 2 Steps (R2S) Method

1) Monte Carlo neutron transport
2) Deterministic activation calculation
3) Monte Carlo γ transport

**INPUT**
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**CODE**
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**OUTPUT**
- Neutron flux and spectra map

Neutron flux $n/cm^2s$

Neutron spectrum

![Diagram showing neutron flux and spectrum](image-url)
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- MCNP Input File
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- Material
- Irradiation Scenario
- Decay Time

**CODE**
- MCNP5 - N
- FISPACT

**OUTPUT**
- Neutron flux and spectra map
- Activity map
- $\gamma$ source
Rigorous 2 Steps (R2S) Method

1) Monte Carlo neutron transport
2) Deterministic activation calculation
3) Monte Carlo $\gamma$ transport

**INPUT**
- MCNP Input File
  - (3D geometry, materials, cross section libraries, neutron source)
- Material
- Irradiation Scenario
- Decay Time
- MCNP Input File
  - (3D geometry, materials, cross section libraries, $\gamma$ source)
  - $\gamma$-to-dose factors

**CODE**
- MCNP5 - N
- FISPACT
- MCNP5 - P

**OUTPUT**
- Neutron flux and spectra map
- Activity map
- $\gamma$ source
- Shutdown dose rate map
Direct 1 Step (D1S) Method

- Substitute Capture with activation-induced radiative decay.
- Neutron and decay $\gamma$ transport treated in a single run.
- Special, ad hoc generated, “capture” cross section data.

Cons:
- Ad hoc libraries should be produced for the activation dose relevant nuclides, so an a priori decision has to be made.
- Each set of libraries is suitable just for 1 cooling interval.
Shutdown Dose Rate Benchmarks

Shutdown Dose Rate Benchmark at FNG\textsuperscript{[3]}

Mock-up of ITER First Wall (Water & Steel IG)

Shutdown Dose Rate Benchmark at JET\textsuperscript{[4]}

In JET benchmark agreement is worse because of the lack of information about the technical drawing (geometry, impurity content)

Agreement between a factor 2 -3

Good experimental vs calculated data agreement


\textsuperscript{[4]} PETRIZZI, L., et al, "Benchmarking of Monte Carlo based shutdown dose rate calculations for applications to JET", ICRS-10, Madeira, 2004
ITER project goals:

- 100 μSv/h \(10^6\) s after the shutdown in the Port Interspace Region \([\phi \approx 10^7\text{n/(cm}^2\text{s})]\) where maintenance is planned.
European Test Blanket Module (TBM) Port

Modules for tritium production tests, containing:
- Breeder (lithium)
- Neutron multiplier to improve efficiency

\[ \text{n+}^6\text{Li} \rightarrow \text{t} + \alpha + 4.8 \text{ MeV} \]
\[ \text{n+}^7\text{Li} \rightarrow \text{n} + \text{t} + \alpha -2.8 \text{ MeV} \]

**Helium Cooled Pebble Bed (HCPB):**
- **Breeder:** lithiated ceramic pebbles (Li$_4$SiO$_4$ or Li$_2$TiO$_3$)
- **Neutron Multiplier:** beryllium pebbles

**Helium Cooled Lithium Lead (HCLL):**
- **Breeder & Neutron Multiplier:** PbLi eutectic (liquid at operating temperatures)
**B-Lite**:  
- Official Model for ITER neutronic analysis  
- Represents 40° sector of the reactor  
- Contains only main components  
- TBM Port represented as an homogenized water-steel block  
- Contains 21216 cells, 27920 surfaces, 26 materials  
- Run 57 histories per second per core (10⁹ histories take 24h using 250 cores)
ITER Model

VERTICAL CUT

HORIZONTAL CUT

x[cm]  y[cm]  z[cm]

PORT PLUG  PORT INTERSPACE  PORT PLUG  PORT INTERSPACE
Calculation performed on rectangular mesh imposed over the geometry (voxel dimensions 10*10*10 cm³)
Jobs run on 600 cores with MPI capability (ENEA cluster CRESCO), time 24 h

- required variance reduction techniques (Weight Windows)
Shutdown Dose Rate in the Maintenance Area Model

- Shutdown Dose Rate exceeds the limit imposed by the ITER project (100 μSv/h 12 days after the shutdown) close to cryostat and Pipe Forest structure.
- Gaps and other experimental ports are the main responsible of the dose.
- Optimization of the gaps and of the experimental port cross talk is currently under investigation.

Impurity content of Steel 316 IG:
- Co60 0.05% wgt – 70% dose
- Ta182 0.01% wgt -22% dose

ACTIVATION GAMMA SOURCE [$\gamma$/cm$^3$s]
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Conclusions

- The worldwide efforts in fusion technology aim at developing, in the long-term, power reactors which can contribute substantially to the supply of electricity.

- The construction and operation of the experimental fusion device ITER (“International Thermonuclear Experimental Reactor”) is an essential next step towards this long-term goal.

- The availability of qualified computational tools and nuclear data for the neutron transport simulation and the calculation of activation and material damage is a pre-requisite to enable reliable design calculations for these facilities.

- An automated R2S shutdown dose rate calculation tool was made and used to evaluate the actual design European TBM Port.

- From preliminary results, the shutdown dose rate in the region of maintenance is higher than 100 μSv/h. The main contribution is due to the cross-talk with the other experimental ports, which must be better described in the MCNP model and further investigated.
Thank You!