Development of Nuclear Analysis Predictive Capabilities for Fusion Energy Systems

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Nuclear Fusion

- Unlike fission where uranium splits generating energy, fusion occurs when two hydrogen nuclei fuse together and release energy.

- Two approaches:
  - Magnetic confinement
  - Inertial confinement
D-T Fusion Represents a Nearly Inexhaustible Energy Source

Fuels: Deuterium: abundant in sea water
Tritium: Half-life~12 years...must be produced?

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Ignition Temperature</th>
<th>Output Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>Product</td>
<td>(millions of °C)</td>
</tr>
<tr>
<td>D + T</td>
<td>4He + n</td>
<td>45</td>
</tr>
</tbody>
</table>

$^6$Li + n $\rightarrow$ T + $^4$He + 4.8 MeV + others

$T_{bred} / T_{burned} > 1$

“Real” fusion fuel cycle:
$^6$Li + D $\rightarrow$ $^4$He + 22.4 MeV

30 Million years of world energy demand in oceans
Fusion Reactors are Complex with Many Components
Central Solenoid
\( \text{Nb}_3\text{Sn}, 6 \text{ modules} \)

Outer Intercoil Structure

Toroidal Field Coil
\( \text{Nb}_3\text{Sn}, 18, \text{ wedged} \)

Poloidal Field Coil
\( \text{Nb-Ti, 6} \)

Machine Gravity Supports
(recently remodelled)

Blanket Module
421 modules

Vacuum Vessel
9 sectors

Cryostat
24 m high x 28 m dia.

Port Plug (IC Heating)
6 heating
3 test blankets
2 limiters/RH rem. diagnostics

Divertor
54 cassettes
Torus Cryopump
8, rearranged
ITER Status

- Agreement signed on November 21, 2006
- Seven parties with more than half of the world population
- Cost ~$7B
- ITER construction starts in 2007 at Cadarache, France
- First plasma in 2016 and 20 year operation
Nuclear Analysis is Essential Part of Design

- Energetic 14 MeV neutrons are emitted in plasma and slowed down and absorbed by surrounding components
- Nuclear analysis for components surrounding the plasma is essential element of fusion nuclear technology
  - Tritium production in breeding blankets to ensure tritium self-sufficiency
  - Nuclear heating (energy deposition) for thermal analysis and cooling requirement
  - Radiation damage in structural material and other sensitive components for lifetime assessment
  - Provide adequate shielding for components (e.g., magnets) and personnel access
  - Activation analysis for safety assessment and radwaste management

- State-of-the-art predictive capabilities (codes and data) are needed to perform required nuclear analyses
There are several numerical methods and codes available to solve the Boltzmann transport equation.

The methods can be broken down into two groups:

- **Deterministic method**: Directly solves the equation using numerical techniques for solving a system of ordinary and partial differential equations.

- **Statistical based method**: Solves the equation using probabilistic and statistical techniques.

Each method has its strengths and weaknesses.
Deterministic Approach

The phase space (space, angle, energy) is discretized

Angle
- $S_n$ - Discrete Ordinates
- $P_1$ - Moment expansion

Energy
- Multi-group (175n-42g)

Spatial discretization
- Finite Element (un-structured meshes)
- Finite Difference (structured equal fine meshes)

Advantages
- Spatial Resolution
- Flux evaluated at a large number of points

Disadvantages
- Angular Quadrature approximation
- Legendre Polynomial expansion of cross-sections
- Ray-Effects for streaming problem
- Group treatment of energy variable
- Require large storage space for multi-dimensional calculations

Codes
- DANTSYS, DOORS. PARTISN code systems (1D, 2D, 3D finite difference)
- ATTLILA (3D finite element with CAD coupling)
**Statistical Monte Carlo Approach**

**Method**
- Use probabilistic and statistical approach to solve transport equation
- The particle travel distance and interaction physics are converted to probabilistic and cumulative distributions, that are sampled using a random number

**Advantages**
- Exact Geometrical representation
- Exact treatment of the transport process
- Exact source-modeling capability
- Continuous (pointwise) energy treatment of the cross-sections

**Disadvantages**
- Require variance reduction techniques to improve accuracy
- Usually cannot generate accurate results at all locations
- Many particle histories and large CPU time to obtain accurate results

**Codes**
- MCNP, MCNPX, MORSE, TRIPOLI, TART
**Method**
Solve rate equations for radioactive nuclide production and decay to determine radioactive inventory, decay heat, biological dose, and radwaste

**Codes**
- ALARA
- DKR-PULSAR
- REAC2
- RACC
- FISPACT
- ORIGN2
- ANITA
- ACAB
- ACT4
Evaluated nuclear data include raw data that needs processing to produce working libraries for use with nuclear analysis codes:

- **US**: ENDF/B-IV, -V, -VI, -VII
- ENDF/B-VII released Dec 15, 2006
- **Japan**: JENDL-3.2, JENDL-3.3
- **EU**: JEFF-3.1
- **RF**: BROND-2.1

**Processing Codes**: NJOY, TRANSX, AMPX

- Process data in either Multi-group or continuous energy format
- In addition to basic transport and scattering cross sections, special reaction cross sections are generated:
  - Kerma factors - for nuclear energy deposition
  - Damage energy cross sections - for atomic displacement (dpa)
  - Gas production (tritium, helium, hydrogen)
FENDL-2.1 is Reference International Fusion Nuclear Data Library

<table>
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<tr>
<th>No.</th>
<th>Library</th>
<th>NMAT</th>
<th>Materials</th>
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<tbody>
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<td>1</td>
<td>ENDF/B-VI.8 (E6)</td>
<td>40</td>
<td>$^2$H, $^3$H, $^4$He, $^6$Li, $^7$Li, $^9$Be, $^{10}$B, $^{11}$B, $^{16}$O, $^{19}$F, $^{28-30}$Si, $^{31}$P, S, $^{35,37}$Cl, K, $^{50,52-54}$Cr, $^{54,57,58}$Fe, $^{59}$Co, $^{61,62,64}$Ni, $^{63,65}$Cu, $^{197}$Au, $^{206-208}$Pb, $^{209}$Bi, $^{182-184,186}$W</td>
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<td>2</td>
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<td>3</td>
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<td>Mg, Ca, Ga</td>
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<td>4</td>
<td>JENDL-FF (JFF)</td>
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<td>$^{12}$C, $^{14}$N, Zr, $^{92}$Nb</td>
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<td>5</td>
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<td>6</td>
<td>BROND-2.1 (BR2)</td>
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<td>$^{15}$N, Sn</td>
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</table>
Developed Innovative Monte Carlo Tool
MCNP-CGM

• Direct use of solid model geometry in MCNP
  – Use Common Geometry Module (CGM) to interface MCNP *directly* to CAD & other geometry data

• Production experience
  – ARIES-CS
  – HAPL
  – ITER FWS
Motivations

• Reduce impacts of manual conversion of 3-D model data
  – Time
  – Simplifications
  – Errors

• Extend richness of geometric representation
Application to ARIES-CS
Compact Stellarator

• Geometry complex varying in both poloidal and toroidal directions
• Cannot be modeled by standard MCNP

Examined effect of helical geometry and non-uniform blanket and divertor on total TBR and nuclear heating
NWL Maps (colormaps in MW/m²)

5 cm SOL

30 cm SOL

uniform src

Radiative heating

Poloidal Angle (degrees)

Toroidal Angle (degrees)

X max

X max
Neutron Flux in Laser Beam Duct

SiC GIMM

Flux (n/cm²s)

M3

M2
ITER Benchmark

- 40 degree machine sector
- Used for validation of MCNP/CAD tool
- 802 cells
- 9834 surfaces
- 17 material specifications
ITER Benchmark

• Comparing 4 results
  – Neutron wall loading
  – Divertor fluxes and heating
  – Magnet heating
  – Midplane port shielding/streaming

• Participants
  – UW, FZK, ASIPP, JAEA
Neutron Wall Loading : results

Poloidal Distance [cm]

Neutron Wall Loading [MW/m²]

- Segmented
- by FW/S module

Source Input Table
TF Coils: results

Nuclear Heating (W)

<table>
<thead>
<tr>
<th></th>
<th>Neutron</th>
<th>Photon</th>
<th>Total</th>
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<tbody>
<tr>
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<td>1.39 ± 0.05</td>
<td>17.0 ± 0.6</td>
<td>18.4 ± 0.6</td>
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<td>0.06</td>
<td>2.47 ± 0.06</td>
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<td>3.82 ± 0.04</td>
<td>44.6 ± 0.4</td>
<td>48.4 ± 0.5</td>
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<td>65.6 ± 0.9</td>
<td>71.6 ± 1.0</td>
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<td>3.38 ± 0.04</td>
<td>40.9 ± 0.5</td>
<td>44.3 ± 0.6</td>
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<td>2.27 ± 0.04</td>
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<td>0.08</td>
<td>3.66 ± 0.08</td>
<td>45.7 ± 1.3</td>
<td>49.4 ± 1.4</td>
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<td>0.05</td>
<td>1.88 ± 0.05</td>
<td>24.0 ± 0.7</td>
<td>25.9 ± 0.7</td>
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<tr>
<td></td>
<td>35.5 ± 0.2</td>
<td>415 ± 2.3</td>
<td>450 ± 2.5</td>
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</tbody>
</table>

8.1 kW in all TF I/B legs
ITER First Wall/Shield
Module 13 Mockup

Model generated by designers using common tools facilitates analysis
FWS results
Summary

- Nuclear fusion systems are geometrically complex with many components requiring detailed 3-D nuclear analysis.
- An innovative calculation method was developed where the 3-D Monte Carlo neutronics calculations are performed directly in the detailed CAD geometrical model.
- This eliminates human error, improves accuracy and cuts down turnaround time to accommodate design changes and iterations.
- The tool has been successfully tested for an ITER benchmark and applied to perform nuclear analysis for several fusion designs.
Questions?

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