DYN3D –
New Developments in NURISP

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Overview

• **WP 1.2 – Advanced deterministic methods**
  – Data interface between APOLLO 2.8 and DYN3D
  – Development and integration of the advanced DYN3D-SP3
  – Integration of flexible PPR on SALOME platform

• **WP 1.3 – Advanced few-group XS libraries generation**
  – Implementation of a new method for consideration of spectral history effects

• **WP 1.4 – Benchmarking**

• **WP 1.5 – User’s training for DYN3D**
Achievements in NURISP - DYN3D
Neutronic solvers

Rectangular

Hexagonal

Trigonal

Diffusion + SP3

Diffusion

Diffusion + SP3

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Achievements in NURISP - DYN3D
Methodology for XS preparation

HELIOS

APOLLO 2.8

Modification of SAPHYB browser

SERPENT (outside of NURISP)

Consideration of spectral history effects during burn-up
**Achievements in NURISP Integration into SALOME**

- Full integration of DYN3D into SALOME by API (Application Programming Interface)
- Input deck generation by interactive graphical pre-processor

- Implementation of the new pin power reconstruction model into the DYN3D. Extension of the DYN3D-module API to provide the new PPR capabilities. Preparation for advanced code coupling (DYN3D – FLICA)

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Data interface between APOLLO 2.8 and DYN3D

NEMTAB library format

- Multidimensional interpolation tables (ASCII format)
- Based on OECD/NEA and U.S. NRC PWR MOX/UO₂ Core Transient Benchmark
- 5D
  - Burn-up
  - Moderator density
  - Boron concentration
  - Fuel temperature
  - Moderator temperature
- Reading subroutine is included in DYN3D
  - Internal library number IWQS=22
Data interface between APOLLO 2.8 and DYN3D

SAPHYB browser
- Convert APOLLO2 output into NEMTAB library format
- Developed by CEA, modified by UPM
- Modified by HZDR for SPH-factors calculation

SPH factors
- Correction of homogenization error
- Calculated by DYN3D automatically in iterative way using fluxes from transport (APOLLO, HELIOS) solution
- SPH-factors are stored in NEMTAB library
The DYN3D code

DYN3D is a 3D nodal code with thermal-hydraulic feedback

- Steady-state and transient analyses of LWRs
- Square and hexagonal fuel assembly geometries
- Two-group and multi-group versions

Available neutronic solvers

- Square, hexagonal, and trigonal diffusion
- Square and trigonal simplified $P_3$ ($SP_3$) neutron transport

Motivation for DYN3D-$SP_3$ in trigonal geometry

- More accurate than $P_1$
- Applicable to reactors with hexagonal fuel assemblies
- Allows for flexible mesh refinement
- Core modeling with asymmetric assemblies

Development of the advanced DYN3D-$SP_3$
The SP$_3$ transport approximation

Spherical harmonics ($P_N$) approximation:
- Expansion of the angular flux in spherical harmonics up to the order $N$
- Occurrence of a large number of complex equations (multi-dim.)

Simplified $P_N$ (SP$_N$) approximation:
- Multi-dimensional generalization of 1D $P_N$ equations
  - $\rightarrow$ Legendre expansion of the angular flux
- Less computational expensive than $P_N$ approximation
- More accurate than diffusion ($\sim P_1$) approximation

SP$_3$ equations:

$$- D_0 \Delta \Phi_0 (\vec{r}) + \Sigma_{r_0} \Phi_0 (\vec{r}) - 2 \Sigma_{r_0} \Phi_2 (r) = S_0 (r)$$
$$- D_2 \Delta \Phi_2 (\vec{r}) - \frac{2}{5} \Sigma_{r_0} \Phi_0 (\vec{r}) + \left( \frac{4}{5} \Sigma_{r_0} + \Sigma_{r_2} \right) \Phi_2 (\vec{r}) = - \frac{2}{5} S_0 (\vec{r})$$

Pair of coupled diffusion-type equations
DYN3D – nodal solution on triangular geometry

Nodal expansion approach:

Innernodal flux solution as sum of

Specific solution of the inhomogeneous diffusion equation

General solution of the homogeneous equation (Helmholtz equations)

Orthonormal polynomials up to second order

Exponential functions

\[
\Phi_n^{A/B r} (x, y) = \sum_{k=0}^{3} c_{nk} h_k^{A/B} (x, y) + \sum_{j=1}^{2} \varepsilon_{nj} \sum_{l=1}^{3} d_{jl} \exp( B_j e_{l+1} \cdot r )
\]

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Verification analysis

Reference fuel assembly
- Represented by 1536 trigonal nodes
- 151 fuel pins
- 18 guide tubes
- Presence of absorber rods
- reference solution with HELIOS code
Verification analysis

- DYN3D-DIF (8 gr.): 5.0% deviation from reference
- DYN3D-SP$_3$ (8 gr.): 1.2% deviation from reference

Normalized nodal powers and deviations from reference solution obtained by DYN3D-DIF and DYN3D-SP$_3$ (2- and 8-energy-group structure)

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Development of the advanced DYN3D-SP3

Pin-wise calculations for color set (NURISP PWR lattice code benchmark)

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>SP3</th>
<th>SP3 with SPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOX 4.0 37.5 GWd/t</td>
<td>UOX 4.2 0.15 GWd/t</td>
<td>UOX 4.2 0.15 GWd/t CR inserted</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HELIOS-DYN3D</th>
<th>Diffusion</th>
<th>SP3</th>
<th>SP3 SPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δkeff, pcm</td>
<td>930</td>
<td>342</td>
<td>145</td>
</tr>
<tr>
<td>ΔPinPow, %</td>
<td>12</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>SD, %</td>
<td>2.1</td>
<td>1.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

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The work was performed in collaboration with KIT (Karlsruhe).

**Armando Gomez (KIT):**
- Implementation of the new pin power reconstruction model into the DYN3D Fortran sources. Adding and modifying of subroutines and data structures.

**Andre Gommlisch (HZDR):**
- Extension of the existing DYN3D-module API to provide the new PPR capabilities.
  - Introduction of a new mesh creation and data mapping.
Integration the advanced DYN3D with PPR

**DYN3D PPR domain**

- New flexible setup of the PPR domain under study.
- Possible assignment of different assemblies of choice.
- Less impact to the existing DYN3D input structure.

```
$ Start of PPR setup
FLUX RECONSTRUCTION
$NREC
  5
$ IX  IY
$ Central FA
    0  0
$ South East
    1 -1
$ North East
    1  1
$ North West
  -1  1
$ South West
  -1 -1
$ IPRN
    1
$ End of PPR setup
```
Integration the advanced DYN3D with PPR

DYN3D-Module

- New mesh generator for pin by pin refinement of investigated assemblies.

- Advanced data mapping to MED fields for data exchange in case of code coupling and data visualization.

- Preparation for advanced code coupling (DYN3D – FLICA)
Integration of the advanced DYN3D with PPR

Result visualization on the NURESIM platform

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Integration the advanced DYN3D with PPR

Example 1: Minicore 25 FA, CR Ejection at HZP in 0.1 sec

$t = 0.001\,\text{s}$
$t = 0.020\,\text{s}$
$t = 0.050\,\text{s}$
$t = 0.100\,\text{s}$
$t = 0.200\,\text{s}$
Integration the advanced DYN3D with PPR

Example 2: PWR Boron Dilution Benchmark

Refinement in bottom-left quadrant

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Advanced few-group XS libraries generation

\section*{History effects in DYN3D}

\begin{itemize}
  \item History changes of homogenized cross sections are proportional to history change of Pu\(^9\) concentration

  \[ \Sigma_{\text{actual}} = \Sigma_{\text{base}} \cdot \left[ 1 + k_h \left( \sqrt{\frac{N_{\text{Pu}}}{N_{\text{Pu}}^{\text{nominal}}}} - 1 \right) \right] \]

  \item The Pu-based historical correction decreases errors in single-assembly multiplication factor at least in one order of magnitude

  \item Method is proven for UOX, MOX and BA fuel for PWR and hexagonal fuel for VVER
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{deviation_plot}
\caption{Deviation of \(k_{\infty}\) from the reference value (HELIOS) without and with correction for spectral history effects}
\end{figure}

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History effects in DYN3D

- Application of Pu-correction results in power redistribution to upper part of reactor
- Power redistribution results in axial burnup distribution
- Burnup redistribution results in core criticality and length of the equilibrium cycle

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Thanks for your attention.